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Prof Dr. Mehmet Ozaslan

Department of Biology, Gaziantep University, Türkiye

Website: mehmetozaslan.com

E-mail: ozaslanmd@gantep.edu.tr

Language Editor

Lecturer Ceren Dogan

School of Foreign Languages, Necmettin Erbakan University, Türkiye

Email: cerendogan@erbakan.edu.tr

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The aim of the conference is to bring together researchers and administrators from different countries, and to discuss theoretical and practical issues in all fields of Engineering, Technology and Basic Sciences.

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Correlation of Polyphenols, Pectin Substances and Antioxidant Activity of Persimmon Fruits (*Diospyros kaki* L.) According to Ripening Stage and Processing Conditions

Merabi Ardzenadze

Batumi Shota Rustaveli State University

Aleko Kalandia

Batumi Shota Rustaveli State University

Darejan Chikovani

Batumi Shota Rustaveli State University

Elene Kamadadze

Batumi Shota Rustaveli State University

Meri Khakhutaishvili

Batumi Shota Rustaveli State University

Inga Kartsivadze

Batumi Shota Rustaveli State University

Abstract: Persimmon (*Diospyros kaki*), a member of the Ebenaceae family, has been cultivated in Georgia since the 1950s, with an annual production of approximately 50,000 tons. Among the commercially important cultivars, the astringent 'Hachiya' and the non-astringent 'Hyakume' are predominant. Persimmon fruits are characterized by high nutritional value and are rich in bioactive compounds, particularly phenolic compounds and dietary fiber. The present study investigated the chemical composition and antioxidant capacity of 'Hachiya' and 'Hyakume' fruits at different stages of ripeness and after various pre-treatments (CO₂ exposure, freezing, and thermal treatment). The quantitative determination included sugars, total polyphenols, pectin substances, titratable acidity, vitamin C, carotenoids, cellulose, total nitrogen, and protein content. Significant variability in phenolic compounds and pectin fractions was observed during ripening and following pre-treatment. A correlation between pectin content and tannin-related astringency was established. During ripening, the formation of insoluble pectin-tannin complexes reduced the level of soluble tannins and consequently decreased bitterness. Antioxidant activity, evaluated by DPPH and ABTS assays, was strongly correlated with total polyphenol content. Overall, both ripening stage and pre-treatment significantly affect the chemical composition and antioxidant potential of persimmon fruits. Fruits at the technical ripeness stage represent a particularly rich source of polyphenolic compounds, especially tannins, which may largely determine the health-promoting properties of persimmon.

Keywords: Persimmon, Polyphenols, Pectin substances, Antioxidant activity, Ripening

Introduction

Persimmon (*Diospyros kaki* L.), a member of the Ebenaceae family, was originally cultivated in China and Japan and is now grown worldwide, with 90% of global production concentrated in China, Japan, and Korea. World persimmon production amounts to approximately five million tons annually. In Georgia, persimmons are widely

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distributed in the Black Sea coastal regions (Giordani, 2002; Denev & Yordanov, 2013; Ardzenadze et al., 2018). The fruit develops initially with a greenish color; as it matures, chlorophyll is degraded and carotenoids alter its color from yellow to orange. The color of the skin and consistency of the pulp serve as indicators of ripeness (Salvador et al., 2006).

Two primary types of persimmons are recognized: astringent and non-astringent. Astringent varieties have a high content of soluble tannins. Persimmon fruits are classified according to their tannin content: fruits containing 0.1–0.2% tannins are slightly astringent, those with less than 0.1% are virtually non-astringent, and fruits with more than 0.2% tannins are highly astringent. Astringency results from the binding of soluble tannins to salivary proteins, producing a rough sensation in the mouth.

Persimmon fruits are rich in a diverse array of nutrients and phytochemicals, including carbohydrates, vitamins, proanthocyanidins, flavonoid oligomers, tannins, phenolic acids, dietary fiber, and carotenoids, which contribute significantly to their flavor, color, and nutritional and medicinal value. Total phenolic content varies between cultivars and is characterized by high levels of dietary fiber, tannins, polyphenols, flavonoids, and carotenoids (Yoo et al., 2019; Suzuki et al., 2015; Del Bubba et al., 2009).

The accumulation of biologically active substances and the physiological activity of persimmon fruits depend on variety and time of harvest. The stage of maturity is a critical factor determining organoleptic and functional properties and significantly affects the concentration of phenolic compounds (Senter et al., 1991; Kondo et al., 2004; Baltacıoğlu & Artik, 2013).

Dietary antioxidants, particularly phenolic compounds, play an important role in preventing oxidation of low-density lipoprotein cholesterol (LDL-C) and inhibiting the development of atherosclerosis. A diet rich in vegetables and fruits is associated with significantly reduced coronary artery mortality (Hertog et al., 1993; Paganga et al., 1999). Dietary fiber has been linked to the prevention and treatment of several conditions, including diverticular and coronary heart disease (Anderson et al., 1994; Grigelmo-Miguel et al., 1999).

There is substantial evidence that antioxidants in food sources play a critical role in maintaining health and preventing disease. Natural antioxidants have attracted increasing interest, as they can provide bioactive compounds capable of preventing many chronic diseases. Processing or industrialization through jams, jellies, juices, dried persimmons, spirits, and vinegars is one approach to increase accessibility to consumers and add value to the final product (González et al., 2015; Sharma et al., 2017; Ardzenadze et al., 2025).

Although persimmon fruit contains significant amounts of biologically active compounds, difficulties often arise in the production of products with high organoleptic characteristics. It is therefore necessary to study the variability in polyphenol and pectin content in relation to ripening and varietal characteristics to facilitate rational selection of raw materials. Various technological processing methods are needed to produce pastes, purées, and glucose–fructose extracts with selected physicochemical and organoleptic properties.

Astringency can be effectively reduced by soaking in warm water, which promotes binding and precipitation of tannins with endogenous macromolecules. CO₂ treatment inhibits aerobic respiration and forces anaerobic respiration, leading to acetaldehyde accumulation, insoluble complex formation, and elimination of astringency. Furthermore, astringency can also be reduced by freezing and thawing, even though acetaldehyde accumulates in only small quantities under these conditions (Ding et al., 2025; Ozdemir et al., 2020; Han et al., 2022).

The aim of this study was to investigate changes in the composition of phenolic and pectin substances in two persimmon varieties grown in Adjara (Black Sea region of Georgia) during on-tree ripening and after harvesting under different processing conditions.

Materials and Methods

Plant Material and Sample Collection

For the purposes of this study, persimmon (*Diospyros kaki* L.) ‘Hachiya’ and ‘Hyakume’ varieties were collected in the Khelvachauri municipality (Akhalsheeni) of the Adjara region, Georgia, in the 2025 harvest year. Selection criteria included a yellow-green hue at the early stage of ripening, a pronounced yellow-orange hue at the harvest (technical ripeness) stage, and a dense texture. To study variation in phenolic compound content at different ripening stages, analytical samples were taken from the same trees every 15 days. For processing experiments,

'Hachiya' fruits were sorted by size (170–200 g), color uniformity, and absence of surface defects. Fruits were divided into four batches of 20 fruits each and subjected to: (1) untreated harvest-stage control; (2) CO₂ atmosphere (88%) for 60 h; (3) hot water treatment at 45°C for 12 h; (4) freezing at –20°C for 20 h. After processing, juice and pomace were obtained by direct pressing.

Chemicals

The following reagents were used: Folin–Ciocalteu's phenol reagent (Sigma-Aldrich, BCCH3316), 2,2-diphenyl-1-picrylhydrazyl (DPPH) (Sigma-Aldrich), vanillin (Sigma-Aldrich, V1104-100G), chlorogenic acid (Sigma-Aldrich, Lot#SLBJ3632V), caffeic acid (ROTH, Art. Nr. 5869.3), (+)-catechin hydrate (Biosynth, FC30661), β -carotene (Sigma-Aldrich, C4582), n-hexane (Merck, CAS-No: 110-54-3), acetic acid (Merck, CAS-No: 64-19-7), methanol (Roth, Art.-Nr. 8388.6).

Standard Methods of Chemical Analysis

Dry matter was determined by the thermogravimetric method; water-soluble dry matter using a digital refractometer (Carl Zeiss, Germany); total titratable acidity and pH using an automatic titrator (Mettler-Toledo AG, Switzerland) with 0.1 N NaOH titration against malic acid. Sugars and pectin fractions were determined according to AOAC Official Methods (Association of Official Analytical Chemists, 2005; John Bean Technologies Corporation, 2011).

Determination of Polyphenolic Substances

Tannins in persimmon fruit are present in both free (soluble) and bound (insoluble) forms, determined by oxidation with potassium permanganate in the presence of indigo carmine. A 25.0 g analytical sample was weighed, transferred to a 250 mL volumetric flask, extracted with 200 mL water at 80°C for 30 min, made up to 250 mL, filtered, and the free tannin percentage (Extract I) was determined. For bound tannins, 10 mL of 1% NaOH was added to the residue, extraction was performed under reflux, and the extract was neutralized with 1% H₂SO₄ and made up to 250 mL (Extract II). In both cases, 10 mL of extract was titrated with 0.1 N KMnO₄ in the presence of indigo carmine until the blue color turned amber, using the conversion coefficient 0.004157.

Total Phenolic Content

Total phenolic content was determined by the Folin–Ciocalteu method: 1 mL Folin–Ciocalteu reagent was added to 1 mL extract, followed after 3 min by 1 mL of 10% Na₂CO₃, and the volume was made up to 10 mL. Absorbance was measured at 750 nm after 90 min. Results were expressed as chlorogenic acid equivalents (mg/g sample) (Datuashvili et al., 2025; Surmanidze et al., 2024).

Total Phenolic Acid Content

Total phenolic acids were determined spectrophotometrically: 250 μ L of extract was mixed with 250 μ L of 0.1% ethanolic HCl and 4.55 mL of 2% HCl, vortexed, incubated for 15 min, and absorbance was measured at 320 nm. Results were expressed as caffeic acid equivalents (mg/g sample) (Abashidze et al., 2024).

Total Flavonoid Content

Flavonoids were determined by the AlCl₃ spectrophotometric method. One mL of extract was mixed with 5 mL H₂O and 0.3 mL of 5% NaNO₂ (5 min incubation), followed by 0.3 mL of 10% AlCl₃ (6 min), and 2 mL of 1N NaOH. Absorbance was measured at 510 nm and results were expressed as quercetin equivalents (mg/g sample) (Abashidze et al., 2024; Datuashvili et al., 2025).

Catechin and Leucoanthocyanin Determination

Catechins were determined using the vanillin reagent method; 3 mL vanillin reagent was added to 1 mL extract and absorbance measured at 500 nm after 3 min, with results recalculated from a (+)-catechin calibration curve (Surmanidze et al., 2024). For leucoanthocyanins, 8 mL leucoanthocyanidin reagent was added to 1 mL extract; a parallel unheated sample served as blank while the heated sample (40 min) was measured at 550 nm, expressed as cyanidin-3-O-glucoside equivalents (mg/g dry weight) (Datuashvili et al., 2025).

Antioxidant Activity

DPPH radical-scavenging activity was measured at 517 nm after 30 min dark incubation. The half-maximal inhibitory concentration (IC_{50}) was determined by four-parameter logistic regression and expressed as mg dry sample per 50% inhibition (Brand-Williams et al., 1995; Surmanidze et al., 2024). ABTS⁺ decolorization activity was measured at 734 nm after 6 min, with the working solution adjusted to an absorbance of 0.70 ± 0.02 ; IC_{50} was determined by the same method (Re et al., 1999).

Statistical Analysis

All analyses were performed in triplicate. Data are presented as mean $\pm$ standard deviation. Statistical significance was evaluated at $p \leq 0.05$ using Microsoft Excel.

Results and Discussion

Tannin Content During Ripening

The dynamics of soluble, bound (insoluble), and total tannin content during on-tree ripening are presented in Figures 1 and 2 for the ‘Hachiya’ and ‘Hyakume’ varieties, respectively. In both cultivars, a pronounced and progressive decline in total tannin content was observed throughout the ripening period (October–December 2025), consistent with the well-documented destringency process in persimmon (Del Bubba et al., 2009; Denev & Yordanov, 2013).

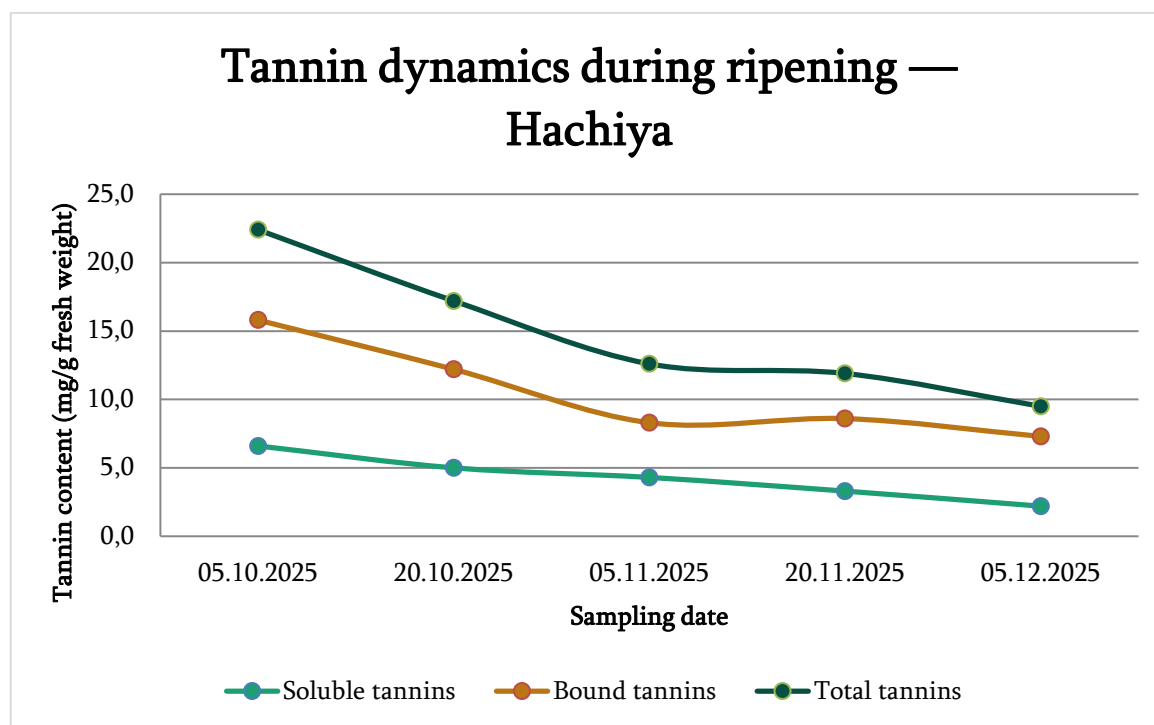


Figure 1. Tannin dynamics during ripening — ‘Hachiya’ cultivar (mg/g fresh weight)

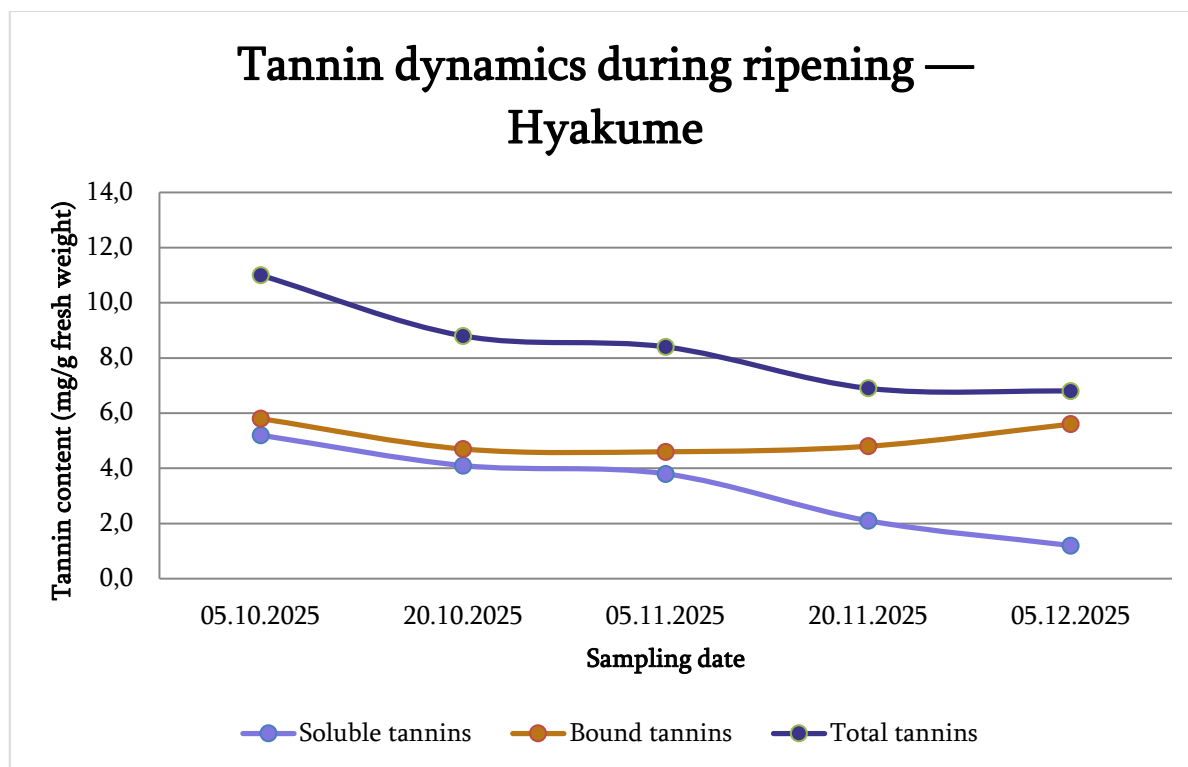


Figure 2. Tannin dynamics during ripening — ‘Hyakume’ cultivar (mg/g fresh weight)

At the early (unripe) stage, soluble tannins predominated and were present at their highest concentrations, conferring strong astringency to the fruit. As ripening progressed, the content of soluble tannins decreased markedly — by approximately 80% relative to initial values — while bound (insoluble) tannin fractions also declined, though less steeply, by up to 50%. This transition reflects the polymerization and complexation of tannins with endogenous proteins and polysaccharides, particularly pectin, rendering them insoluble and organoleptically inactive (Denev & Yordanov, 2013).

The ‘Hachiya’ cultivar exhibited consistently higher total tannin concentrations compared to ‘Hyakume’ across all sampling dates, in agreement with the classification of persimmon cultivars based on tannin content and astringency. These findings confirm that ripening stage is a primary determinant of persimmon astringency and must be carefully considered when selecting fruit for processing

Pectin Fractions During Ripening

The quantitative dynamics of soluble pectin, protopectin, and total pectin content during the ripening process are presented in Figures 3 and 4. For both varieties, a consistent decline in total pectin was observed from October to December, amounting to approximately 68% in ‘Hachiya’ (from 2.79 to 0.90 g/100g) and approximately 21% in ‘Hyakume’ (from 7.05 to 5.60 g/100g). Notably, ‘Hyakume’ contained substantially higher pectin concentrations at all ripening stages, which may be associated with structural differences between astringent and non-astringent cultivars in cell wall composition.

At the technical ripeness stage (early October), protopectin clearly exceeded soluble pectin in ‘Hachiya’ (2.32 vs. 0.47 g/100g), reflecting the predominance of the water-insoluble, high-methoxyl pectin fraction typical of unripe fruit. As ripening advanced, protopectin underwent hydrolytic degradation, progressively releasing soluble pectin chains. By physiological maturity, the soluble fraction accounted for a greater relative proportion of total pectin, consistent with fruit softening.

Of particular relevance is the relationship between pectin and tannin dynamics. The formation of insoluble pectin–tannin complexes during ripening is considered one of the principal mechanisms responsible for natural deastringency: soluble tannins are sequestered by pectin macromolecules, forming insoluble aggregates that no longer interact with salivary proteins (Del Bubba et al., 2009; Denev & Yordanov, 2013). The parallel decline of

both soluble tannins (Figures 1 and 2) and total pectin (Figures 3 and 4) over the ripening period supports this mechanistic interpretation. It underlines the functional interdependence of these two phytochemical classes.

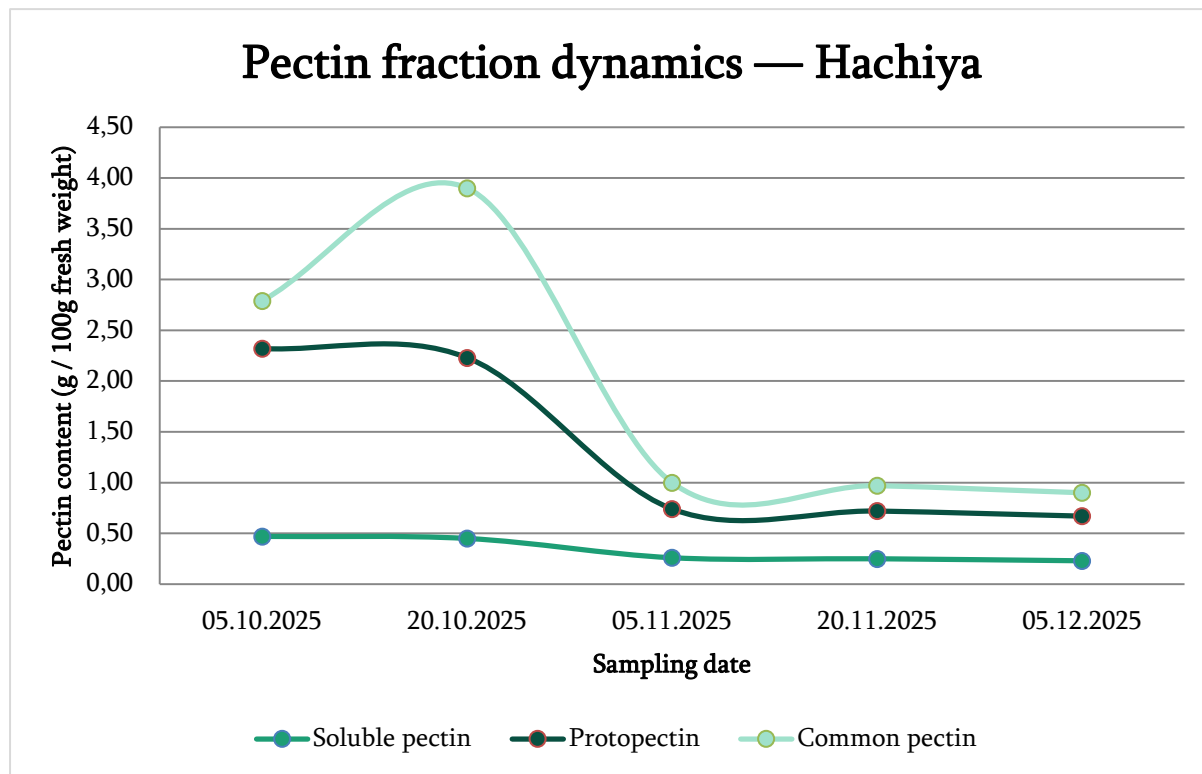


Figure 3. Pectin fraction dynamics during ripening — ‘Hachiya’ (g/100g fresh weight, mean $\pm$ SD)

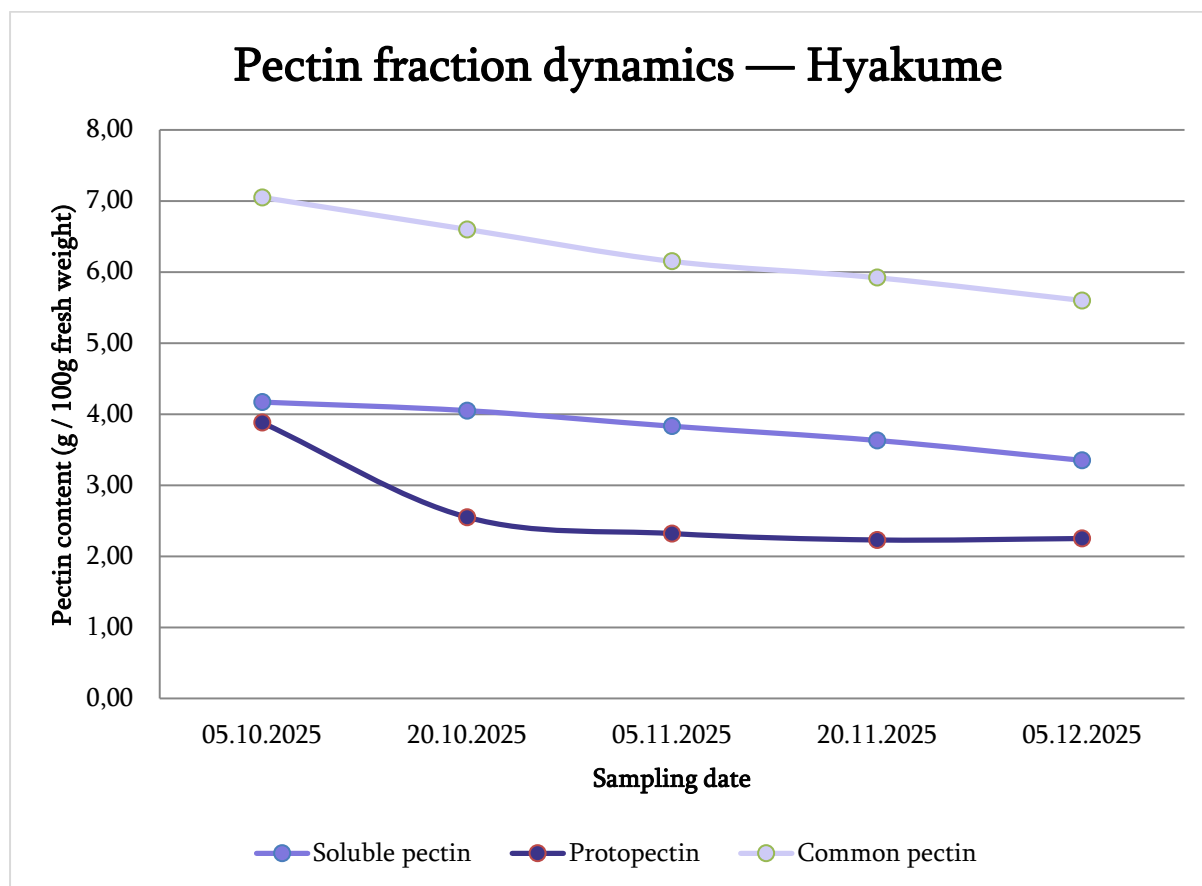


Figure 4. Pectin fraction dynamics during ripening — ‘Hyakume’ (g/100g fresh weight, mean $\pm$ SD)

Phenolic Compound Profile at Commercial Harvest

Table 1. Phenolic compound composition of ‘Hachiya’ and ‘Hyakume’ persimmon fruits at commercial harvest stage (mg/g fresh weight)

Cultivar	Total phenols	Phenolic acids	Total flavonoids	Catechins	Leucoanthocyanins
Hachiya	8.210	0.144	6.162	1.227	3.990
Hyakume	5.770	0.108	3.986	0.623	1.964

The concentrations of individual phenolic fractions in ‘Hachiya’ and ‘Hyakume’ fruits at the commercial harvest stage are presented in Table 1. The ‘Hachiya’ variety exhibited significantly higher total phenolic content (8.210 mg/g) compared to ‘Hyakume’ (5.770 mg/g), reflecting the characteristic chemical distinction between astringent and non-astringent cultivars. Similar differences have been reported by other authors (Suzuki et al., 2005).

In both varieties, total flavonoids constituted the dominant phenolic fraction — 6.162 mg/g in ‘Hachiya’ and 3.986 mg/g in ‘Hyakume’ — followed by leucoanthocyanins (proanthocyanidins): 3.990 and 1.964 mg/g, respectively. Catechin concentrations were also notably higher in ‘Hachiya’ (1.227 vs. 0.623 mg/g). Phenolic acids represented the smallest fraction in both varieties (0.144 and 0.108 mg/g), consistent with the literature describing persimmon polyphenols as predominantly flavanolic in character (Jiménez-Sánchez et al., 2015; Yoo et al., 2019). These data were used as baseline indicators for evaluating subsequent technological processing variants.

Physicochemical Characteristics at the Optimal Harvest Stage

Based on the tannin and pectin dynamics described above, 20 November 2025 was identified as the optimal harvest window corresponding to the technical (commercial) ripeness stage, most suitable for production of glucose–fructose syrups and phenolic-rich extracts. Physico-chemical parameters of both varieties at this stage are presented in Table 2.

Table 2. Physicochemical characteristics of ‘Hachiya’ and ‘Hyakume’ persimmon fruits at the optimal harvest stage (20 November 2025)

Indicator	Hachiya	Hyakume
Dry matter, %	19.4 ± 0.58	15.88 ± 0.57
pH	6.03 ± 0.20	6.0 ± 0.18
Titrateable acidity, %	0.10 ± 0.003	0.11 ± 0.003
Invert sugar, %	15.88 ± 0.53	11.9 ± 0.35
Sucrose, %	1.12 ± 0.03	0.9 ± 0.03
Ascorbic acid, mg/100g	30.23 ± 0.90	35.0 ± 1.05
Carotenoids, mg/100g	32.25 ± 0.96	29.47 ± 0.88

Dry matter content was $19.4 \pm 0.58\%$ for ‘Hachiya’ and $15.88 \pm 0.57\%$ for ‘Hyakume’. Both varieties showed very low titrateable acidity (0.10–0.11%), indicative of a mild, sweet flavor profile favorable for syrup production. Invert sugar content was substantially higher in ‘Hachiya’ ($15.88 \pm 0.53\%$) than in ‘Hyakume’ ($11.9 \pm 0.35\%$), with glucose and fructose together accounting for 92–93% of total sugars in both cultivars, making this fraction well-suited for glucose–fructose syrup recovery without prior hydrolysis. Ascorbic acid content was slightly higher in ‘Hyakume’ (35.0 ± 1.05 mg/100g), while carotenoid concentrations were higher in ‘Hachiya’ (32.25 vs. 29.47 mg/100g). The near-neutral pH (approximately 6.0 for both varieties) confirms the suitability of this harvest stage for processing into stable, high-quality purées and extracts.

Effect of Processing Conditions on Phenolic Content and Antioxidant Activity

The influence of four processing methods on total phenolic content (TPC) and antioxidant activity (DPPH and ABTS IC₅₀) of ‘Hachiya’ fruit is summarized in Table 3. Results are presented separately for the juice and pomace fractions. A strongly negative correlation between TPC and IC₅₀ was confirmed across all treatment variants: the lower the IC₅₀, the stronger the radical-scavenging capacity, consistent with published data (Park et al., 2008; Jang et al., 2010; Jang et al., 2011).

Table 3. Effect of processing conditions on phenolic content and antioxidant activity of ‘Hachiya’ persimmon fruit

Processing method	Fraction	TPC (mg/g)	DPPH IC ₅₀ (mg)	ABTS IC ₅₀ (mg)
Fruit — harvest stage (control)	Fruit	8.21	1.52	1.26
Direct pressing	Juice	2.04	5.79	4.75
	Pomace	5.17	2.25	1.98
Warm water treatment 45°C/12h	Juice	3.73	5.08	4.15
	Pomace	3.80	4.75	3.28
CO ₂ treatment 88%/60h	Juice	1.30	13.04	10.27
	Pomace	7.04	1.17	0.87
Freezing -18°C/20h	Juice	4.62	5.86	5.00
	Pomace	3.42	3.01	2.36

The unprocessed fruit at the harvest stage showed the highest TPC (8.21 mg/g) and the strongest antioxidant activity (DPPH IC₅₀ = 1.52 mg; ABTS IC₅₀ = 1.26 mg), serving as the reference level for all processing comparisons. Direct pressing resulted in pronounced partitioning of phenolics: the pomace (TPC 5.17 mg/g; DPPH IC₅₀ = 2.25 mg) retained substantially more phenolics than the juice (TPC 2.04 mg/g; DPPH IC₅₀ = 5.79 mg), confirming that high-molecular-weight tannins and proanthocyanidins remain preferentially associated with the cell wall matrix.

Warm water treatment (45°C/12 h) led to a relative equalization of TPC between juice (3.73 mg/g) and pomace (3.80 mg/g) fractions, both showing intermediate antioxidant activity (DPPH IC₅₀ = 5.08 and 4.75 mg, respectively). This equalization likely reflects thermal degradation of high-molecular-weight tannins and their partial extraction into the aqueous phase.

CO₂ treatment (88%/60 h) produced the most divergent fractionation. The CO₂-treated juice exhibited the lowest TPC of all variants (1.30 mg/g) and the weakest antioxidant activity (DPPH IC₅₀ = 13.04 mg; ABTS IC₅₀ = 10.27 mg). In contrast, the CO₂-treated pomace retained the highest TPC of all processed fractions (7.04 mg/g) with the strongest antioxidant capacity among processed samples (DPPH IC₅₀ = 1.17 mg; ABTS IC₅₀ = 0.87 mg), approaching that of the control fruit. This redistribution reflects the CO₂ deastringency mechanism: anaerobic conditions promote acetaldehyde accumulation, driving polymerization of soluble tannins into insoluble complexes retained in the solid phase (Ding et al., 2025; Ozdemir et al., 2020; Han et al., 2022).

Freezing (-18°C/20 h) yielded an intermediate pattern, with TPC of 4.62 mg/g (juice) and 3.42 mg/g (pomace), and DPPH IC₅₀ values of 5.86 and 3.01 mg, respectively. Collectively, these results demonstrate that processing type determines not only the quantitative distribution of phenolic compounds between fractions, but also has a significant impact on their antioxidant properties. The CO₂-treated pomace is identified as the most phenolic-rich and antioxidant-potent fraction, with direct implications for valorization of persimmon processing by-products.

Conclusion

The present study provides information on the chemical composition of fruits of two persimmon varieties grown in Georgia, examining qualitative and quantitative variation in phenolic compound content at different stages of physiological ripening and under different processing methods (freezing, warm water treatment, and CO₂ treatment). The stage of ripening, as well as the type of technological intervention, essentially determines both the fractional distribution of phenolic compounds and antioxidant activity, ultimately affecting the functional and bioactive value of the product. Fruits at the stage of commercial harvest are a richer source of polyphenolic compounds, in particular soluble tannins. Such fruits can be used for the extraction of tannins, which have a wide range of biological activity. Fruits processed by various methods can be used for the preparation of pastes and glucose–fructose extracts. The CO₂-treated pomace in particular represents a high-value fraction with exceptional polyphenol retention and antioxidant potential, warranting further investigation for functional food and nutraceutical applications.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in the EPSTEM journal belongs to the authors. No ethics committee approval was required for this study, as it involved laboratory analysis of plant material only.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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Author(s) Information

Merabi Ardzenadze

Batumi Shota Rustaveli State University
6010 Batumi, Georgia
Contact e-mail: merab.ardzenadze@bsu.edu.ge
ORCID iD: <https://orcid.org/0000-0002-5398-7617>

Aleko Kalandia

Batumi Shota Rustaveli State University
6010 Batumi, Georgia
ORCID iD: <https://orcid.org/0000-0001-9570-9263>

Darejan Chikovani

Batumi Shota Rustaveli State University
6010 Batumi, Georgia
ORCID iD: <https://orcid.org/0000-0001-6651-4475>

Elene Kamadadze

Batumi Shota Rustaveli State University
6010 Batumi, Georgia
ORCID iD: <https://orcid.org/0009-0004-4743-5535>

Meri Khakhutaishvili

Batumi Shota Rustaveli State University
6010 Batumi, Georgia
ORCID iD: <https://orcid.org/0009-0008-1202-4145>

Inga Kartsivadze

Batumi Shota Rustaveli State University
6010 Batumi, Georgia
ORCID iD: <https://orcid.org/0009-0007-4254-0717>

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The Physical Nature and Structural Organization of Steel Surface Layers Formed Under Thermal Deformational Effect Caused by Pulsed Laser Radiation

Elena Shcherbakova

Don State Technical University

Sergey Knyazev

Don State Technical University

Abstract: During pulsed laser processing and modification of the surface of steels and alloys, several still unresolved issues arise related to the structure formation and property development in the irradiated zones. The aim of this article is to study and scientifically analyze the features in phase transformations, structure and properties formation of the steels surface layers under variable modes of high-speed laser heat treatment. Metallophysical studies in the work were carried out on samples of carbon and alloy steels subjected to pulsed laser irradiation using a technological device Kvant-16 with a radiation power density of 50–250 MW/m². The identification of the phase composition and the materials structure study were carried out by several methods: metallographic, X-ray, scanning probe microscopy, hardness measurement. It is shown that the locality of laser treatment, a high heating rate and high temperature gradients along the layer depth led to the thermoelastic stresses appearance, which play the main role in the steels surface hardening. The physical nature and structural organization of the “white zone” formed around carbide inclusions in steel have been established by metallophysical studies. The main part of the “white zone” is a nanosized austenite-martensite structure with a martensite lath size of ~150nm, which has anomalously high values of microhardness. It has been established that under the conditions of pulsed laser radiation thermal-deformation effect during the treatment of steels and alloys without surface melting, the main role in structure formation and formation of properties is played not by diffusion processes, but by processes of local plastic deformation. It is shown that the presence in laser-hardened steel of a dispersed carbides large amount (more than 40% of the irradiated volume of steel), surrounded by “white zones”, contributes to the creation of a structural state on the working surfaces of products with high microhardness values.

Keywords: Laser irradiation, Steels, Carbides, Structure.

Introduction

Pulsed laser treatment has a number of characteristic features that affect the processes of hardening, structure formation, and the formation of the irradiated material operational properties. These include the high concentration of the supplied energy and the treated domain locality; high manufacturability; high processing speed; ease of automation; absence of hazardous waste during irradiation, etc. (Cui et al., 2019; Katancik et al., 2020; Lapouge et al., 2019; Lesyk et al., 2017; Roy et al., 2017; Sagar et al., 2018). The developed surface of such a structure, consisting of low-angle, semi-coherent, low-energy boundaries, determines the low etchiness of the “white zone”, which has anomalously high values of microhardness.

An analysis of the prospects and relevance using the laser processing for hardening various materials showed that pulsed laser radiation has unique characteristics that allow heating the materials surface at hyper high

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speeds (106 deg/s) and with almost complete absence of holding at temperatures above critical points. Subsequent rapid cooling at rates of 104-106 deg/s fixes in the material surface layers some results of phase transformations and structure formation occurring in them at high heating temperatures.

Non-trivial thermal processes lead to the temperature gradients' appearance and the formation of hardened zones with a depth of 0.05-0.18 mm on the steels surface, which have low etching, dispersed crystalline structure, and high hardness. The result of laser treatment depends on the energy characteristics of the heat source, the time of its exposure, and the thermo physical properties of the material being hardened.

To determine the structural and tool steels hyper speed heat treatment technological prospects, the article provides a scientific analysis of the features in phase transformations and structure formation, the formation of properties in the steels surface layers under variable modes of high-speed laser heat treatment.

The created and considered physical models of the phenomena that arise in materials during laser processing will make it possible to purposefully form in the surface layers of steels the necessary, specified structure with the required level of performance properties.

Features of the laser processing process- locality (spot diameter ~1-5 mm), small depth of heat-affected zones (~50-150 microns), high heating and cooling rates - leave an imprint on the structures formed in the surface layers of materials.

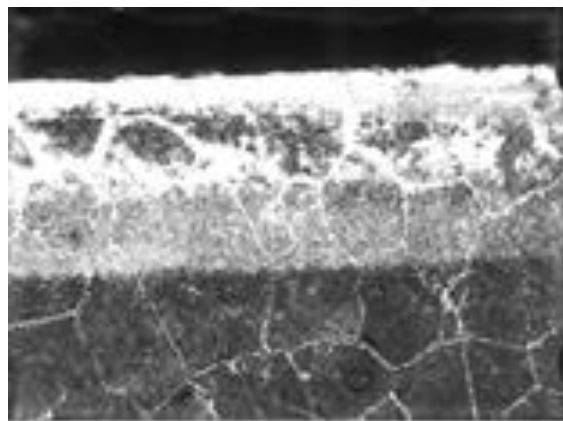
Method

The materials for this study were carbon and alloy steel.

Pulsed laser irradiation was carried out on the technological device: "Kvant-16". Changing the radiation energy, the beam defocusing degree (3-6 mm), the duration of the radiation (1-6) 10^{-3} s made it possible to vary the radiation power density in a wide range (50-250 MW/m²). The identification of the phase composition and the study of the materials structure after laser processing were carried out by several methods, the combination of which was determined by the research objectives: metallographic, X-ray, study of areas of laser processing using a scanning probe microscope in atomic force microscopy mode, hardness measurement, etc.

Results and Discussion

When carrying out metallophysical studies, it was found that in the irradiated layer of steel, as can be seen in Figure 1, two zones are formed that have a different phase transformations nature. On the surface of the material there is a fusion zone, which is formed during crystallization under laser hardening from a liquid state. It has a dendritic structure, and the dendrites are directed towards the heat sink. In this zone, carbides are almost completely dissolved, and there are no such defects in the liquid metal as craters, slag inclusions, decarburized areas of the slick. The zone of laser hardening from the liquid state is absent in the case of laser processing without melting the metal surface.



x 250

Figure 1. Structure of laser-irradiated zones on steel: U12

Below there is a zone of laser hardening from a solid state, which has a low etching rate and the highest hardness. It was established (Parkin & Zhatkin, 1994) that an important, although not decisive, role in the process of structure formation during high-speed laser processing is played by mass transfer and its special case - diffusion. This is especially true for multiphase steels and alloys, containing a significant carbides amount, the dissolution of which, at least partially, affects the saturation degree of α - and γ - solid solutions with carbon and alloying elements, on the course of phase transformations, on the level of the irradiated materials achieved properties.

It should be noted that, under laser heating conditions, high values of temperature gradients and concentrations, as well as the presence of stress fields, play an important role in the process of structure formation in the irradiated metal. It was found that under pulsed laser irradiation, under time deficit conditions, diffusion processes are observed only in the zones of laser quenching from the liquid state, at the boundary with the quenching zone from the solid state, and in the “carbide - steel matrix” compositions in the material zones irradiated without fusion.

The temperature gradients and thermal stresses that appear in the metal zones irradiated with fusion of the surface contribute to the dynamic convective mixing of the liquid at a speed of 103cm/s, and also, despite the extremely short laser pulse time (10^{-3} s), partial or complete dissolution of carbides.

As a result, the chemical composition of the fused metal changes, the points of martensitic transformation decrease, and a significant amount of textured metastable retained austenite (40-70%) is fixed, which is characterized by a high dispersity of the structure (cross-section of dendrites 5-9 nm) and crystallization texture.

As mentioned above, the irradiated zones have a heterogeneous structure in depth, along with the zone of laser hardening from the liquid state; there is a zone of laser hardening from the solid state. The peculiarities of this zone are its non-etching in conventional reagents, dispersion of the structure and high hardness. The low etching of this zone is apparently associated with the low energy of the interphase boundaries, as well as with the absence of the phase boundaries decoration with dispersed carbide inclusions.

To elucidate the fine structure features of the laser hardening zone from the solid (austenitic) state and the role of mass transfer in its formation, annealed samples of U8 carbon steel after laser hardening were studied using a Hitachi TM-1000 scanning electron microscope, which makes it possible to obtain an undistorted image of the surface metal in reflected and secondary electrons with a high magnification and a depth of field exceeding the optical microscope depth of field, and also allows you to obtain a profile of the investigated surface.

First of all, attention is drawn to the results of the local chemical analysis for the irradiated zones, shown in Figure 2. As can be seen, the chemical composition of the solid state laser hardening zone is similar to the chemical composition of the base metal, that is, there are no explicit macro-diffusion processes in this zone. Despite this, the irradiated steel in this zone has properties that differ from the base metal. For comparison, Figure 2 (b) shows the chemical composition of steel irradiated with melting. As can be seen, with an almost complete dissolution of carbides, the general background and the reflections intensity of alloying elements increase, which indicates the occurrence of diffusion processes in this case. Of interest is the fine structure of the solid-state laser hardening zone (SS zone).

Figure 3 shows the microstructure of the transition zone from the base metal (lamellar pearlite) to the SS zone, as well as the distribution of the surface profile heights in the base metal and in the SS zone. The route of scanning and measuring the height of structural elements is indicated in Figure 3 (a) with a marker line. As can be seen: the SS zone has a dispersed, poorly etched structure; individual elements of the structure cannot be detected at a magnification of 100,000 times.

A change in the contrast of the image, which makes it possible to distinguish between the base metal and the SS zone when examined with a scanning electron microscope, may be associated with a local change in the chemical composition at the interface between ferrite and cementite. This is explained by the possible escape of carbon atoms from the boundaries of cementite plates to dislocations of the adjacent ferrite, which leads to a change in the conditions for the interaction of the probe electron beam with these microvolumes of steel. One of the possible reasons for the local change in the chemical composition at the cementite-ferrite boundaries is the difference in the binding energy of carbon atoms with iron atoms in the crystal lattice of cementite in comparison with their binding energy with dislocation cores.

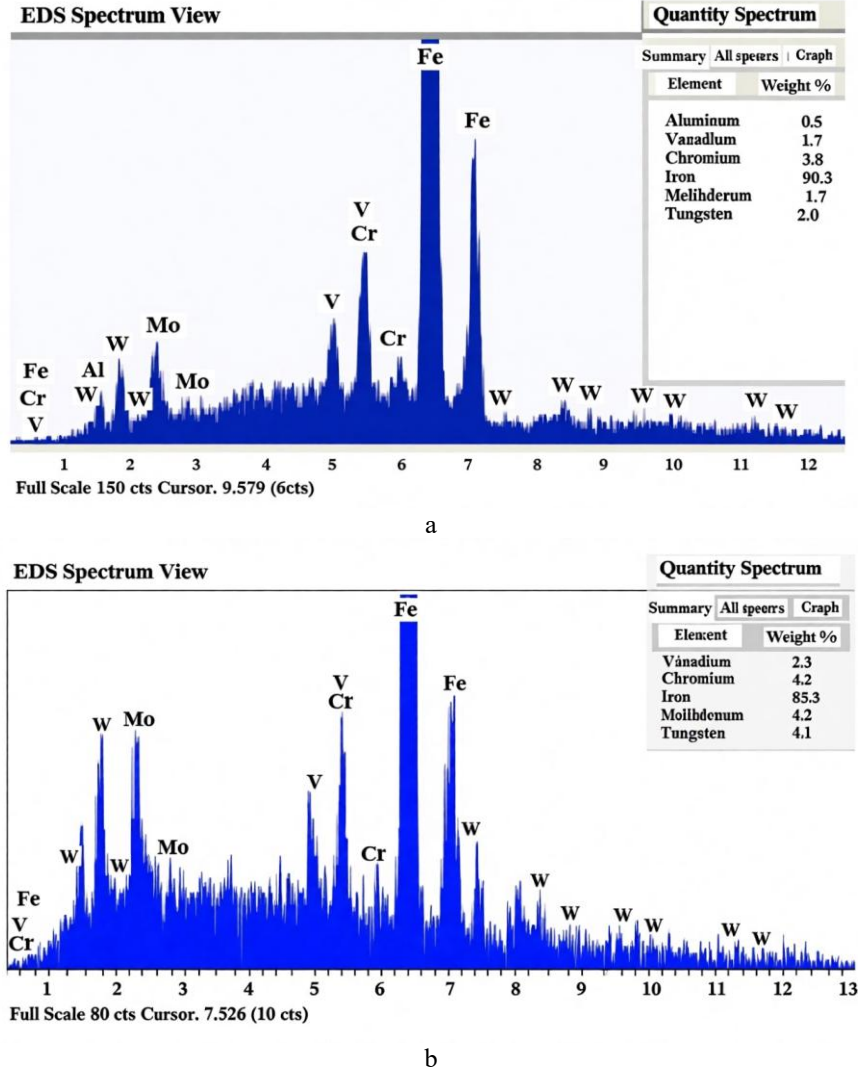


Figure 2. Local spectral analysis of U8 steel after laser irradiation without (a) melting and (b) surface melting.

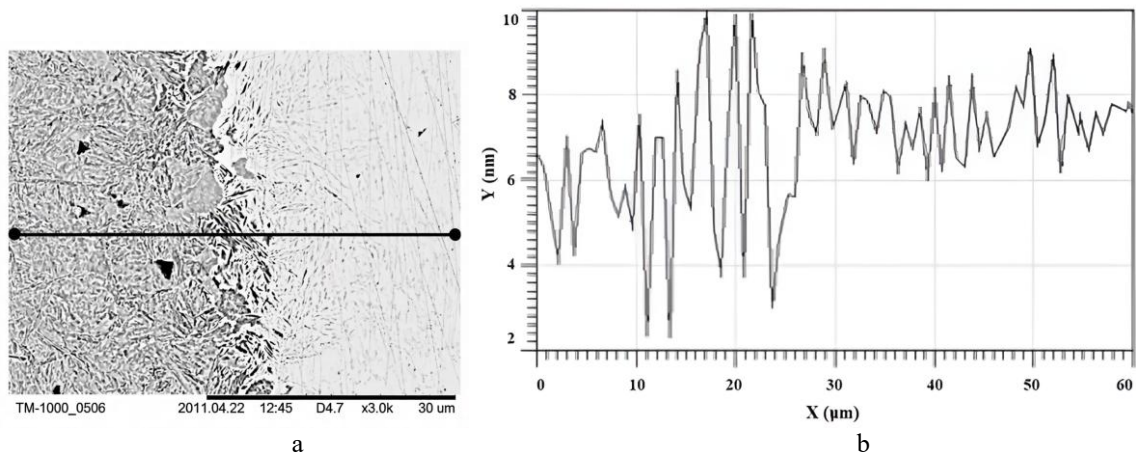


Figure 3. Microstructure of the transition domain from the base metal to the SS zone of the irradiated spot on U8 steel with the lamellar pearlite structure, revealed during the study on SEM (a) and the profilogram indicated by the line of the transition zone (b).

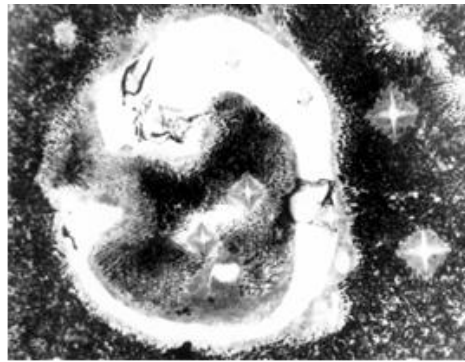
It was found that the metal regions in the SS zone are located above the plane of the thin section, that is, they are harder and more dispersed. The profilogram of this domain does not have sharp fluctuations in height, that is, the transition zones between the matrix and the carbide protruding above the surface of the microsection are smoothed out. As can be seen in Figure 4 (b), in the initial lamellar pearlite, the average height of the sample

surface profile is 6.2 nm, and in the SS zone - 7.4 nm. This result, as well as the fact that the chemical composition of the SS zone is practically similar to the chemical composition of the parent metal, may indicate a partial dissolution of carbides, which begins from the interface between them and the ferrite matrix.

In order to expand knowledge about the fine structure and properties of the SS zone, scratch wear tests were carried out using the Nanotest installation. A friction probe equipped with a strain gauge was used, which made it possible to determine the friction force between the indenter and the sample under the action of the gravity of the calibration weights.

It has been established that the values of the friction force when the SS zone is scratched by the indenter are 17 MN in comparison with 11 MN for the base metal. It can be concluded that the SS zone is formed at a pulsed thermal-deformation stress of the laser-irradiated metal surface layer. In this case, local plastic deformation occurs, accompanied by dynamic polygonization and quenching of the matrix surrounding the carbides with a possible change in the chemical composition in local domains of the structure at the boundaries of the "carbide - steel matrix" composition. Moreover, different mechanisms are responsible for the degree and result of the changing the chemical compositions processes and mass transfers processes in the SS zone and in the laser-melted metal discussed above.

Let us consider the features of the mass transfer manifestation during laser processing without melting the metal surface. When carrying out metallographic studies, it was noticed that in the laser irradiation zone of alloy steel, despite the short thermal effect duration, the results of the partial carbides dissolution process in the surrounding matrix are clearly visible. As can be seen in Figure 4, this is expressed in the formation of a light non-etched border around the carbide inclusions, the so-called "white zones".



x500
Figure 4. "White zones" around carbides in irradiated steel R6M5.

The micro hardness of these areas is 4-6 GPa. The obtained values of hardness correspond to the hardness of medium-carbon steels martensite. The ensembles formation of such concentration inhomogeneous areas in the irradiated zones additionally strengthens the laser-hardened metal.

It can be concluded that the light non-etched border near the carbide particles indicates the austenite formation during heating and martensite formation during cooling these areas.

The carbon spread from the carbides grain boundaries occurred at a distance of $L=2-3$ microns. This diffusion path during the action of the laser beam $\tau \approx 10^{-3}$ s corresponds to the diffusion coefficient of carbon in austenite $D \approx L^2/\tau \approx 4 \cdot 10^{-5} \text{cm}^2/\text{s}$, which exceeds the value of the carbon diffusion coefficient in iron (1-5) $10^{-7} \text{cm}^2/\text{s}$ at a temperature of 1000°C and corresponds to the self-diffusion coefficient of iron in the melt.

Such a high diffusion rate of carbon can be explained by the appearance of the liquid phase interlayers at the boundaries of carbides with a matrix (with ferrite) due to contact melting, which occurs at temperatures much lower than the melting temperatures of the components during the thermo-force stresses action at the "carbide-ferrite" boundaries under laser irradiation.

A similar contact melting phenomenon at the boundary of cementite inclusions with a matrix of technical iron was described for the case of laser irradiation in (Dolgachev et al., 2024; Pustovoi et al., 2017) and graphite with a metallic matrix of cast iron in (Li & Guan, 2020). As a result, a complex structural pattern is formed around the carbide inclusions. In the immediate vicinity of the boundary, due to contact melting, a thin shell of

liquid metal is formed, which promotes the accelerated mass transfer of carbon atoms and alloying elements from the inclusions to the adjacent matrix layer.

After crystallization around carbides, the formation of a superhard amorphous-like framework is possible. It should be noted that, depending on the heating temperatures reached during the action of the laser pulse, different mass transfer driving forces can prevail in the irradiated metal. At high temperatures, the main mechanism is thermal diffusion caused by high temperature gradients (10^5 - 10^7 K/cm), which is effective for 7-10 ms. Beginning from 700-800°C, deformation processes, heterogeneous in depth, intensively proceed. During this time period, anomalous accelerated mass transfer occurs, associated with the influence of local microplastic deformation processes occurring in the zones of laser treatment from the solid state (Brover & Shcherbakova, 2023, 2024; Kumar et al., 2023; Lu et al., 2019; Sahoo et al., 2023).

In the main part of the volume of "white zones", the transformation of $\alpha \rightarrow \gamma$ under the described extreme temperature-force conditions is carried out according to the shear mechanism, which leads to plastic deformation of the matrix. Under conditions of high-speed laser hardening, the recrystallization processes are suppressed, the dynamic polygonization processes of austenite proceed with the fragmented substructure formation. Austenite crystals are in the form of thin plates separated by semi-coherent boundaries with low energy and high density of epitaxial dislocations (Li et al., 2023; Ma et al., 2022; Tsumura et al., 2025).

In the process of high-speed quenching, an $\alpha \rightarrow \gamma$ transformation occurs in the austenite rim. Martensite crystals are shear-formed in austenite lamellae and are also in the form of thin lamellas separated by low-energy semi-coherent boundaries. This leads to a low etching of the "white zone" and a very high microhardness (10-12 GPa) due to the high density of dislocations during shear $\alpha \rightarrow \gamma \rightarrow \alpha$ transformations. Figure 5 shows the results of studying the "white zone" structure using an atomic force microscope.

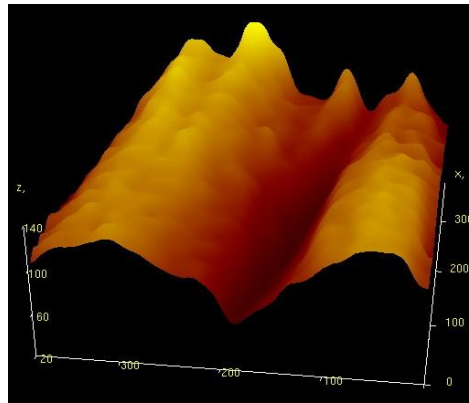


Figure 5. 3D - image of the "white zone" structure (AFM)

As can be seen in the 3D image, martensite crystals have the form of thin laths ~ 150 nm in size and look like protrusions on the surface. The troughs are, apparently, thin wedge-shaped twins, which are formed during diffusionless phase transformations of the martensitic type at the elastic twinning stage (Brover & Shcherbakova, 2023; Kraposhin, 1989; Matyunin et al., 2022). The presence in laser-hardened steel of a dispersed carbides large amount (more than 40% of the irradiated steel volume), surrounded by "white zones", contributes to creation on the working surfaces of products the structural state with high microhardness values, indifferent to external temperature-force loading during operation.

It has been experimentally established that the revealed the structural state features of the steels and alloys irradiated surface layers make it possible, by varying the parameters of the laser radiation mode, to obtain structures in them that have different degrees of adaptation to external loading conditions and have a positive effect on heat and wear resistance.

Conclusion

1. It has been established that under the conditions of pulsed laser radiation thermal-deformation effect during the treatment of steels and alloys without surface melting, the main role in structure formation and formation of properties is played not by diffusion processes, but by processes of local plastic deformation. Which is the

relaxation consequence of thermostrictive stresses and stresses at the phase boundaries in the "carbide-steel matrix" system.

2. It is shown that the presence in laser-hardened steel of a dispersed carbides large amount (more than 40% of the irradiated volume of steel), surrounded by "white zones", contributes to the creation of a structural state on the working surfaces of products with high microhardness values.

3. The possibilities of improving the methods of thermal hardening of materials using pulsed laser heating have been determined. This makes it possible to solve the problem of forming the surface layer structure with varying degrees of adaptability to the temperature-force conditions loading both during irradiation and during operation.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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Author(s) Information

Elena Shcherbakova

Don State Technical University
Gagarina Sq.,1, Rostov-on-Don, Russian Federation, 344003
ORCID iD: <https://orcid.org/0000-0002-9239-1955>
*Contact e-mail: etsherbakova@donstu.ru

Sergey Knyazev

Don State Technical University
Gagarina Sq.,1, Rostov-on-Don, Russian Federation, 344003
ORCID iD: <https://orcid.org/0000-0002-8607-3416>

*Corresponding author(s) contact email

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Utilization of Defatted and Phenolic-Extracted Grape Pomace Flour in Bakery Products: Valorization and Functional Potential

Khatuna Diasamidze

BAU International University Batumi
Batumi Shota Rustaveli State University

Inga Kartsivadze

Batumi Shota Rustaveli State University

Indira Djafaridze

Batumi Shota Rustaveli State University

Maia Vanidze

Batumi Shota Rustaveli State University

Aleko Kalandia

Batumi Shota Rustaveli State University

Abstract: Grape pomace is a high-volume by-product of wine production, whose thorough valorization is of particular importance for the modern circular bioeconomy and the sustainable development of the agri-food sector. The present study aims to evaluate the potential of flour obtained from grape pomace for application in bakery products. After the removal of oil and the main phenolic fraction, the resulting flour is characterized by a high dietary fiber content and is considered a promising raw material for improving the structural parameters of dough and the functional–technological properties of the final products. The incorporation of such flour into bakery formulations offers the possibility to simultaneously reduce reliance on conventional flours and increase the intake of dietary fiber and bioactive components, which is in line with current scientific and technological trends in the development of functional and sustainable food products. This approach, on the one hand, highlights the specific technological potential of defatted and phenolic-extracted grape pomace flour and, on the other hand, strengthens the integration of wine-making by-products into the value chain as a source of high value-added ingredients for the food industry.

Keywords: Circular bioeconomy, Grape pomace flour, Valorization

Introduction

Grapes are among the most widely cultivated crops worldwide, with global production estimated at over 79 million tons in 2018, according to the Food and Agriculture Organization (FAO) of the United Nations. Consumption of grapes has been associated with beneficial effects on human health owing to their high content of bioactive compounds. Approximately 75% of the grapes produced globally are dedicated to wine production, of which about 20–30% correspond to by-products. These residues are commonly referred to as grape pomace and consist primarily of skins, residual pulp, seeds, and stalks (Flamini et al., 2013; Rodriguez-Lopez et al., 2022).

The management of grape pomace waste poses a significant environmental challenge. Concurrently, consumer demand is rising for natural, health-oriented food ingredients that can supplant synthetic antioxidants and preservatives. The biotechnological potential of grape pomace has spurred extensive research exploring its utility as a fortification agent in food products (Castaldo et al., 2019; Flamini et al., 2013; Rodríguez-López et al., 2022).

In nutraceuticals, the polyphenolic compounds and dietary fiber in grape pomace (GP), and especially in grape seeds underpin its antioxidant, anti-inflammatory, and metabolic health benefits, enabling applications as antioxidant supplements, gut health promoters, weight management aids, and cardiovascular protectants. Although challenges persist regarding sensory modification and bioavailability optimization, GP's versatility and sustainability underscore its potential for innovative, health-focused product development (López-Alarcón & Denicola, 2013; Vanidze et al., 2025; Zhishen et al., 1999).

The escalating global demand for sustainable and innovative solutions in the food and pharmaceutical sectors has intensified efforts to valorize agricultural residues. Winemaking by-products, previously deemed valueless, have attracted considerable interest due to their rich nutritional composition and health-promoting potential. Research has established that these materials are replete with antioxidants, polyphenols, dietary fibers, and other bioactive compounds, which confer diverse benefits such as anti-inflammatory, anticancer, and cardioprotective effects (Castaldo et al., 2019; Rodríguez-López et al., 2022; Vanidze et al., 2025; Zhishen et al., 1999).

The proportion of seeds retained in grape pomace following press extraction is influenced by cultivar, maturation stage, and pressing methodology. On average, seeds constitute approximately 20–25% of the total pomace mass. When the pomace is considered excluding the rachis and skin fraction (i.e., the lignocellulosic skeleton), the relative contribution of seeds increases to approximately 40–50% of the residual mass (Re et al., 1999).

Particular emphasis has been placed on grape seeds as a source of diverse bioactive compounds. Recent research has evinced growing interest in wine production residues—particularly pomace—and their active incorporation into the food industry to enhance product nutritional value. Grape seeds: 35-45% fibers, 10-20% fat, 8-13 % proteins, 5-10% phenols (Flamini et al., 2013; Rodríguez-López et al., 2022).

Study Objective

Incorporation of grape seeds flour (GSF)—derived from Saperavi wine production residues—into wheat flour for bread production, followed by comprehensive analysis of the resultant product.

1. To produce flour from grape seeds.
2. Comparing the quality attributes of a confectionery product formulated with grape seed flour against a wheat flour-based counterpart, thereby identifying its advantages.

Materials

Saperavi grape seeds were collected from the Kakheti region of Eastern Georgia during the 2024 harvest season.

Bread sample preparation

Saperavi grape seeds flour (GSF) (Figure 2) was the third and final fraction of a three-step extraction process: in stage I, the lipid fraction was isolated by mechanical cold-press extraction; in stage II, the phenolic fraction was isolated using ethanol; and in stage III, flour with a high concentration of dietary fiber was obtained, which was used as a functional and low-calorie food ingredient. This approach is consistent with the principle of a circular bioeconomy, where all side streams are integrated into the value chain (Boff et al., 2022; Souza et al., 2024).

Two types of bread were used in the study: a control sample made from 100% wheat flour, and an experimental sample with 10% Saperavi grape seed flour (GSF) (Figure 1). The following parameters were measured: 1. pH, titratable acidity, moisture (Table 1); 2. specific volume and porosity (Table 2); 3. total phenols and flavonoids (Table 3); antioxidant activity by DPPH and ABTS methods (Table 4); 4. the crude protein content in GSF.



Figure 1. GSF



Figure 2. GSF Bread

Methods:

1.1 Method for Determining pH (Active Acidity)

The active acidity (pH) of bread was determined by the potentiometric method according to AACC International Method 02-52.01 (AACC International, n.d.). For this, 10 g of well-ground bread sample was placed in a beaker and 90 ml of distilled water was added. The resulting suspension was mixed for 5 minutes, after a 10-minute delay the pH was measured using a METTLER TOLEDO pH meter. Calibration was performed with standard buffer solutions (pH 4.00 and 7.00). Each sample was measured in triplicate; the result is presented as an average value (Tolve et al., 2021)

1.2 Titratable Acidity Determination Method

Titrate acidity was determined by titrimetric method according to ISO 7230:2007 (International Organization for Standardization, 2007). 10 g of ground bread sample was added to 90 ml of distilled water and intensive mixing was carried out for 5 min. The suspension was filtered; 50 ml of the filtrate was used for titration. 2–3 drops of phenolphthalein indicator (1% ethanolic solution) were added to the sample and titration was carried out with 0.1 N NaOH solution until a faint pink color appeared, which was stable for 30 s. Titrated acidity was calculated as the percentage equivalent of lactic acid according to the following formula (Tolve et al., 2021):

$$\% = (V \times 0.1 \times 0.090 \times 2) / m \times 100$$

Where: V — volume of 0.1 N NaOH used for titration (ml); 0.090 — thousandths of the molar mass of lactic acid (g); 2 — dilution factor (50 ml of 100 ml is used); m — sample mass (g).

1.3 Moisture Determination Method

The moisture content of bread was determined gravimetrically according to AACC International Method 44-19.01 (AACC International, n.d.). Approximately 5 g of bread crumb sample was weighed into a pre-weighed container and placed in an oven at $105 \pm 2^\circ\text{C}$. The sample was dried to constant weight (3–4 hours). The moisture content was calculated using the following formula (Tolve et al., 2021):

$$\text{Moisture (\%)} = (m_1 - m_2) / m_1 \times 100$$

Where: m_1 — mass of sample before drying (g); m_2 — mass of sample after drying (g).

Each sample was analyzed in triplicate.

2.1 Determination of Bread Specific Volume:

The specific volume of bread was determined using the seed displacement method according to AACC International Method 10-05.01 (AACC International, n.d.). In this method, a bread sample was placed in a half-filled container filled with rapeseed. The difference in seed volume indicated the space occupied by the bread. The specific volume was calculated using the formula (AACC International, n.d.; Tolve et al., 2021):

$$SV = V / m$$

Where: SV — specific volume of bread (cm^3/g); V — volume of bread (cm^3), determined by seed displacement; m — mass of bread (g), determined by analytical balance.

2.2 Determination of Bread Porosity

Bread porosity was determined by the geometric density method (Sapirstein et al., 2007; Tolve et al., 2021). A cylindrical sample with standard parameters was cut from the bread crumb: diameter 3 cm, height 3 cm; since the volume of the cylinder $V = \pi \times r^2 \times h = \pi \times 1.5^2 \times 3 \approx 21.2 \text{ cm}^3$. The mass of the sample (m) was determined using an analytical balance. The density of the sample was calculated:

$$\rho = m / V$$

Bread porosity was calculated by the following formula (Sapirstein et al., 2007):

$$P = (1 - \rho / \rho_0) \times 100$$

Where: P — porosity (%); ρ — bread crumb density (g/cm^3); ρ_0 — the conditional density of the solid phase of bread, taken equal to $1.27 \text{ g}/\text{cm}^3$ — this is a conventional value, widely found in the literature (Besbes et al., 2013; Sapirstein et al., 2007).

3.1. Total Phenols — Folin-Ciocalteu

The total content of phenolic compounds was determined by the standard Folin-Ciocalteu spectrophotometric method. Folin-Ciocalteu reagent (1 ml) and Na_2CO_3 solution (2 ml) were added to 1 ml of the sample extract; incubation was carried out for 1 h at room temperature. The optical density was determined at 760 nm. The results were converted to mg GAE/100 g, on a dry sample (Ieri et al., 2021; Tolve et al., 2021).

3.2. Total Flavonoids — AlCl_3

The determination of flavonoids was carried out by the AlCl_3 spectrophotometric method [20]. 1 ml extract + 5 ml H_2O + 0.3 ml 5% NaNO_2 (5 min) + 0.3 ml 10% AlCl_3 (6 min) + 2 ml 1N NaOH. Op. density — 510 nm. Calibration — quercetin. Results: mg QE/100g, on dry basis (Oprea et al., 2022; Zhishen et al,1999).

3.3. Antioxidant Activity — DPPH IC_{50}

DPPH (2,2-diphenyl-1-picrylhydrazyl) method according to Brand-Williams et al. (1995) Extracts of different concentrations were mixed with 0.1 mM DPPH solution; incubation for 30 min in the dark, room temperature. Op. density — 517 nm. IC_{50} — min. sample mass required for 50% inhibition (mg). Low IC_{50} = strong antioxidant. Results — on dry basis (Hoye & Ross, 2011).

3.4. Antioxidant Activity — ABTS IC_{50}

ABTS^{•+} (2,2'-azino-bis(3-ethylbenzothiazoline-6-sulf. mj.)) method according to Re et al. [15]. ABTS^{•+} — ABTS 7 mM + K₂S₂O₈ 2.45 mM, 12–16 h in the dark. The solution is diluted to OD₇₃₄ = 0.70 ± 0.02. Extract + ABTS^{•+} → inc. 6 min → OD 734 nm. IC_{50} — mg, 50% inhib., dry base. ABTS is sensitive to hydrophilic antioxidants, DPPH — lipophilic; therefore, a combination of the two tests gives a complete picture (Lopez-Alarcon & Denicola, 2013; Re et al., 1999).

4.1. The Crude Protein Content Was Determined by the Eldar Method

The crude protein content was determined by the Eldar method in accordance with the official method of AOAC International (AOAC 976.05) (AOAC International, 2005; Mariotti et al., 2008). The crude protein content was calculated at the expense of total nitrogen ($N \times 6.25$), and the results were expressed as mass on a dry basis (% d.w.).

Results:

Table 1. pH, titratable acidity and moisture

Parameters	White bread (control sample)	GSF bread (+10% seeds flour)
pH active acidity	5,80	5,26
Titratable acidity (%)	0,24	0,32
Moisture (%)	27,84	28,03

pH active acidity - The GSF-enriched bread was characterized by a statistically significant decrease in pH from 5.80 to 5.26 ($\Delta = -0.54$ units) compared to the control sample. Given the logarithmic nature of pH, this 0.54 unit decrease corresponds to a 3.47-fold increase in the H^+ concentration of the aqueous phase ($100.54 = 3.47$). This change is due to the acidic nature of the phenolic compounds contained in GSF - namely gallic acid ($pK_a = 4.4$), ellagic acid ($pK_a = 4.0$) and condensed tannins. These compounds, despite extraction, remain partially covalently bound to the fiber matrix, are distilled during baking heat treatment and reduce pH (Sporin et al., 2018). The pH of the control bread, 5.80, is at the lower end of the normative range (standard white bread: pH 5.8–6.2), while the pH of the GSF bread, 5.26, is within the typical range for functional bread (4.8–5.5) (Hoye & Ross, 2011). This pH range is technologically advantageous, as it helps to increase microbiological stability and optimize fiber hydration.

Titratable acidity - The addition of 10% GPF increases the titratable acidity from 0.24% (2.7°) to 0.32% (3.6°) - 1.33 times. It is noteworthy that the decrease in pH ($H^+ \times 3.47$) significantly exceeds the increase in titratable acidity ($\times 1.33$). This asymmetry is due to the buffering effect of GSF: grape seed proanthocyanidins and tannins, due to their polymeric nature, effectively release H^+ (pH ↓) (Boff et al., 2022; Castaldo et al., 2019). The obtained values are within the standard: control $2.7^\circ \leq GOST\ 27842 \leq 3.0^\circ$; GPF bread $3.6^\circ \leq GOST\ 2077 \leq 4.0^\circ$ (functional bread).

Moisture - The moisture content of GSF bread (28.03%) increased by +0.19 pp compared to the control sample (27.84%). This difference, despite its small size, is technologically important: it is due to the hygroscopic nature of the insoluble dietary fiber of GSF - the fiber replaces gluten proteins during dough formation and reacts with water, increasing the water absorption capacity and retaining more bound water after baking (Iuga & Mironeasa, 2020). In addition, this hydrating effect of fiber has a direct impact on the formation of the gluten network: the GSF particles physically disrupt the continuity of the gluten network - a dilution effect on the protein matrix - which reduces the elasticity of the dough (Iuga & Mironeasa, 2020; Souza et al., 2024).

Table 2. Specific volume, porosity

Parameters	White bread (control sample)	GSF bread (+10% seeds flour)
Specific volume (cm ³ /g)	2,08	1,87
Porosity (%)	61,2	58,2

The inclusion of 10% GSF leads to a 10.1% decrease in the *specific volume* of the bread (from 2.08 to 1.87 cm³/g). This decrease is determined by three interrelated mechanisms. First, the insoluble fiber of GSF

physically disrupts the continuity of the gluten network (dilution effect), reducing the ability of the dough to retain CO₂ during fermentation and baking (Iuga & Mironeasa, 2020). Second, the decrease in pH (from 5.80 to 5.26, Table 1) slightly reduces the metabolic activity of the yeast and, consequently, the intensity of CO₂ production (Sporin et al., 2018). Third, the interaction of phenolic compounds with gluten proteins changes the rheological properties of the dough (Hoye & Ross, 2011). Tolve et al. (2021) reported a similar decrease (from 2.05 to 1.91 cm³/g) with the addition of 10% grape pomace powder, while Oprea et al. (2022) reported a 7% decrease with the addition of 9% GSF. The specific volume of the baseline control sample (2.08 cm³/g) is within the normative range for typical white wheat bread (1.8–2.5 cm³/g), while the GPF bread value (1.87 cm³/g) remains within this range (Tolve et al., 2021).

Porosity in GSF bread was 58.2% compared to 61.2% in the control (–3.0 pp, –4.9%). This difference is directly attributable to the decrease in specific volume—less volume means fewer air pores in the bread structure. Importantly, the porosity of GPF bread (58.2%) remains well above the minimum normative limit (≥ 54%, GOST 28808), confirming the structural acceptability of the product.

Table 3. Total phenols and flavonoids, mg/100g, calculated on dry basis

Sample	Total phenols mg/100g GAE (dry basis)	Total flavonoids mg/100g QE (dry basis)
White bread (control sample)	35,46	21,75
GSF bread (+10% seeds flour)	50,17	32,07

The total phenolic content of the GSF-enriched bread was 50.17 mgGAE/100g, compared to 35.46 mgGAE/100g in the control sample — an increase of +41.5%. Total flavonoids increased from 21.75 to 32.07 mgQE/100g (+47.4%). The proportionally greater increase in flavonoids confirms that GPF is particularly rich in catechins, epicatechin and condensed proanthocyanidins — the dominant bioactive class in grape seed (Flamini et al., 2013). This increase is particularly significant in the context of the preliminary phenolic extraction of GSF: the content of this fraction belongs to fiber-bound phenols — hydroxycinnamic acids, epicatechin and gallic acid esters — which are covalently bound to the fiber matrix and are not extracted by conventional solvent extraction, although they are partially released during baking heat treatment (160–220 °C) (Iuga & Mironeasa, 2020). Tolve et al. (2021) reported a +38% increase in TPC with the addition of 10% grape seeds powder, while Oprea et al. (2022) reported a +45% increase with 9% GSF. Our GSF, a phenolic-extracted flour, gives comparable results to these analogues (+41.5%), which once again confirms the biological importance of fiber-bound phenolic residues.

Table 4. Antioxidant activity — DPPH and ABTS IC₅₀

Sample	Antioxidant activity - 50% inhibition of 0.1 mM DPPH radical by mg of sample on a dry basis	Antioxidant activity - 50% inhibition of ABTS radical using the sample on a dry basis
White bread (control sample)	200,25	177,21
GSF bread (+10% seeds flour)	141,11	105,0

GSF bread showed a statistically significant improvement in antioxidant capacity in both tests. DPPH IC₅₀ decreased from 200.25 to 141.11 mg — –29.5% (×1.42). ABTS IC₅₀ from 177.21 to 105.0 mg — –40.8% (×1.69). The improvement in ABTS (×1.69) is greater than that in DPPH (×1.42) — this asymmetry is chemically informative: the ABTS•⁺ test is sensitive to hydrophilic antioxidants (phenolic acids, hydroxycinnamates, flavones-3-ols), while DPPH is sensitive to lipophilic components (tocopherols, lipophilic flavonoids). Therefore, GSF provides mainly hydrophilic antioxidant contribution, which is consistent with the profile of fiber-bound hydroxycinnamic acids (coumaric, caffeic, ferric) in grape seed (Iuga & Mironeasa, 2020). The antioxidant improvement directly correlates with the results in Table 3: a +41.5% increase in phenolics is accompanied by a –29.5÷40.8% decrease in IC₅₀ (Oprea et al., 2022; Souza et al., 2024; Tolve et al., 2021).

Table 5. The protein content

Sample	GSF	White bread (control sample)	GSF bread (+10% seeds flour)
Protein % (calculated on dry weight)	10	11,23	11,53

The crude protein content in grape seed flour was 10% based on dry weight. This value exceeds the standard norms established for premium wheat flour (11–13 ppm). According to the results, the protein content in standard white bread was 11.23%, while in the GSF bread sample, which was prepared by replacing wheat flakes in bread with grape seed flour (10% mass fraction), the protein content increased to 11.53%.

Discussion

The physicochemical and functional properties of bread fortified with 10% grape seed flour (GSF), a residual fraction from cascade biovalorization of grape pomace, demonstrate coherent alterations attributable to its fiber and residual phenolic components.

Physicochemical Parameters

Incorporation of 10% GSF induces a moderate pH reduction ($\Delta -0.54$), elevated titratable acidity ($\times 1.33$), and marginal moisture increase (+0.19 percentage points), all within normative limits. These shifts arise from the acidic nature of bound phenolics and hydrophilic fiber matrix. Concurrently, fiber disrupts gluten networking, phenolic compounds further acidify the matrix, and elevated moisture collectively diminish specific volume (-10.1%) and porosity (-3.0 percentage points), yet remain physicochemically viable.

Functional and Nutritional Enhancements

GSF substitution yields significant bioactive enrichment, including +41.5% total phenolics and augmented antioxidant capacity (DPPH $\times 1.42$; ABTS $\times 1.69$), derived exclusively from fiber-bound residuals released during baking. Protein content interpretation must account for GSF's dual role as a dietary fiber source and gluten-free ingredient; at 10% inclusion, it proportionally dilutes gluten, conferring nutritional relevance for gluten-sensitive consumers, pending targeted gluten quantification. These findings validate GSF as a third valorization stream—post-extraction of oil (stream I) and phenolics (stream II)—for functional bakery applications.

Conclusion

Incorporation of 10% grape seed flour (GSF), a defatted and phenolic-extracted residual from cascade valorization of grape pomace, produces predictable physicochemical modifications while conferring substantive functional and nutritional benefits. GSF inclusion causes a modest acidification, slight moisture increase, and measurable reductions in specific volume and porosity—effects attributable to the fiber-rich, hydrophilic matrix and residual bound phenolics—but these changes remain within acceptable physicochemical limits for bread quality.

Nutritionally, 10% GSF markedly increases dietary fiber and delivers a significant enrichment of total phenolics and antioxidant capacity (DPPH, ABTS), indicating a potential for improved antioxidant status and associated chronic-disease risk reduction when consumed regularly. The partial dilution of gluten by this gluten-free ingredient may have relevance for formulation of products targeted to gluten-sensitive populations, although targeted gluten quantification is required. Overall, GSF represents a viable tertiary valorization stream for grape pomace with clear applicability in functional bakery products; further work should optimize processing and formulation to mitigate texture losses and should assess bioavailability, sensory acceptability, and long-term health outcomes.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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Author(s) Information

Khatuna Diasamidze

BAU International University Batumi.
Address: Iris Borchashvili Health Center Medina, 237,
Fridon Khalvashi ST, Batumi, 6010, Georgia
Batumi Shota Rustaveli State University. Ninoshvili av. 35,
Batumi, Georgia
ORCID iD: <https://orcid.org/0009-0009-6085-1695>
*Contact e-mail: khatuna.diasamidze16@bsu.edu.ge

Inga Kartsivadze

Batumi Shota Rustaveli State University. Ninoshvili av. 35,
Batumi, Georgia
ORCID iD: <https://orcid.org/0009-0007-4254-0717>

Indira Djafaridze

Batumi Shota Rustaveli State University. Ninoshvili av. 35,
Batumi, Georgia
ORCID iD: <https://orcid.org/0000-0003-2088-212X>

Maia Vanidze

Batumi Shota Rustaveli State University. Ninoshvili av. 35,
Batumi, Georgia
ORCID iD: <https://orcid.org/0000-0003-0807-0735>

Aleko Kalandia

Batumi Shota Rustaveli State University. Ninoshvili av. 35,
Batumi, Georgia
ORCID iD: <https://orcid.org/0000-0001-9570-9263>

*Corresponding author(s) contact email

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Therapeutic Potential of Bioactive Compounds of *Prunus Laurocerasus* in the Management of Metabolic Syndrome

Eteri MargalitadzeAvicenna Batumi Medical University
Batumi Shota Rustaveli State University**Indira Japaridze**

Batumi Shota Rustaveli State University

Maia Vanidze

Batumi Shota Rustaveli State University

Aleko Kalandia

Batumi Shota Rustaveli State University

Nona Surmanidze

Batumi Shota Rustaveli State University

Abstract: *Background:* Obesity and overweight are major global health concerns and it is obvious, that the trend of the cases is growing over time. These states are closely linked to type 2 diabetes mellitus, cardiovascular disease, hypertension, heart failure with preserved ejection fraction and various malignancies. Excess adiposity promotes insulin resistance, chronic inflammation, dyslipidemia, endothelial dysfunction, and neurohormonal activation. Growing interest in natural product-based therapeutics has highlighted polyphenol-rich plant extracts as potential adjunctive strategies for metabolic regulation. Cherry laurel (*Prunus laurocerasus*) is a polyphenol-rich fruit containing bioactive compounds such as quercetin, kaempferol, chlorogenic acid, and anthocyanins with reported anti-obesity effects. *Methods:* Extracts of fresh, frozen, and dried *Prunus laurocerasus* fruits, collected from different regions of Georgia were analyzed for polyphenolic content. The biological activities of the identified bioactive compounds were contextualized based on previously published preclinical studies evaluating their effects on adipogenesis, lipid metabolism, glucose homeostasis, inflammatory signaling and energy regulation. *Results:* All extracts demonstrated consistently high polyphenolic content regardless of processing method or geographic origin. Chlorogenic acid and anthocyanins were identified as the predominant constituents, followed by substantial levels of quercetin and comparatively lower concentrations of kaempferol. *Conclusion:* The polyphenolic profile of *Prunus laurocerasus* suggests its potential as a multifaceted adjunctive strategy in metabolic syndrome management, warranting further translational and clinical investigation.

Keywords: *Prunus laurocerasus*, Metabolic syndrome, Anthocyanins, Chlorogenic acid, Valorization

Introduction

Obesity and overweight currently represent the most significant challenges in global clinical management, with a well-established association between excess adiposity and the rising incidence of type 2 diabetes mellitus (T2D), cardiovascular disease (CVD), and several forms of cancer. These conditions collectively impose a substantial burden on healthcare systems, remaining leading causes of morbidity and mortality worldwide. Since

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1990, childhood and adolescent obesity has increased more than fourfold globally, and in most nations, the prevalence of obesity now exceeds that of being overweight. Currently, approximately 1.4 billion adults are classified as obese, and projections indicate that these trends will continue to escalate by an estimated 30% over the next decade (Chew et al., 2023; O'Neill & O'Driscoll, 2015).

The pathophysiology of obesity is characterized by complex systemic disruptions. Excess adiposity serves as a major independent risk factor for arterial hypertension by increasing sympathetic nervous system activity, activating the renin–angiotensin–aldosterone system (RAAS), and promoting sodium retention (Hall et al., 2015). Furthermore, visceral fat acts as an active endocrine organ, secreting adipokines and inflammatory mediators like TNF- α and IL-6. These cytokines impair endothelial function, increase vascular resistance, and accelerate atherosclerosis by inducing dyslipidemia and chronic inflammation. Consequently, the resulting increase in cardiac workload leads to structural changes such as left ventricular hypertrophy and diastolic dysfunction, often progressing to heart failure with preserved ejection fraction (HFpEF) due to myocardial fibrosis (Seravalle et al., 2017, Lavie et al., 2009, Ridker et al., 2000, Kenchaiah et al., 2002, Packer 2018)

Beyond cardiovascular complications, obesity is the strongest modifiable risk factor for type 2 diabetes (T2D) (Kahn et al., 2006). The expansion of adipose tissue leads to increased free fatty acid release and ectopic lipid accumulation, which triggers chronic inflammation and impairs insulin signaling in skeletal muscle, adipose tissue and the liver (Samuel et al., 2016). Visceral obesity is particularly detrimental, as it is closely associated with β -cell dysfunction and the progression from insulin resistance to overt diabetes (Eckel et al., 2011). Additionally, obesity significantly worsens the prognosis for several malignancies, including colorectal, pancreatic, and postmenopausal breast cancers, leading to higher cancer-related mortality rates (Lauby-Secretain et al., 2016, Calle et al., 2003).

While traditional management approaches, including lifestyle modification and pharmacotherapy, exist, they often provide limited long-term success, and obesity-related mortality remains stubbornly unchanged. This gap in clinical efficacy has fueled growing interest in naturally derived bioactive compounds as complementary strategies. Flavonoids, including quercetin, total phenols, anthocyanins, and kaempferol, offer promising therapeutic potential by targeting inflammatory pathways, enhancing insulin sensitivity, and improving lipid profiles (Godyla-Jabłoński et al., 2024; Oumeddour et al., 2024; Rubio-Ruiz et al., 2019).

In light of this increasing interest in natural product-based therapeutics, the present study investigates the potential benefits of cherry laurel (*Prunus laurocerasus*) bioactive compounds. To address the challenge of seasonal availability, we examined the juice of fresh and frozen fruit, dried products, and processing residues (skin and pomace-waste) from various locations across Georgia. Notably, this research highlights the additional benefit of waste valorization; by demonstrating that processing by-products retain significant bioactive potency, this study supports sustainable strategies for the development of high-value nutraceuticals from agricultural side-streams. Previous studies confirm the rich phytochemical profile and antioxidant potential of *Prunus laurocerasus* extracts (Altuntaş et al., 2018; Konuk et al., 2024; Margalitadze et al., 2025).

While the complexity of metabolic syndrome suggests that dietary interventions are most effective when paired with comprehensive lifestyle changes, preclinical evidence underscores the potent role of specific flavonoids namely quercetin, chlorogenic acid, kaempferol and anthocyanins in improving metabolic health. These compounds exert overlapping anti-inflammatory, antioxidant, and metabolic-regulatory actions through a sophisticated network of molecular signaling (Godyla-Jabłoński et al., 2024; Oumeddour et al., 2024).

As a primary constituent identified in Georgian wild *Prunus laurocerasus* extracts, chlorogenic acid (CGA) plays a pivotal role in the systemic management of metabolic syndrome. CGA primarily targets lipid metabolism by activating the AMPK (adenosine monophosphate-activated protein kinase) pathway. Which leads to increased phosphorylation of acetyl-CoA carboxylase (ACC) to serve a dual purpose: suppression of the *de novo* synthesis of fatty acids and simultaneously promotes lipid oxidation (Oumeddour et al., 2024; Godyla-Jabłoński et al., 2024).

Our focus on CGA is further justified by its impact on hepatic health. In hepatocyte models, CGA has been shown to significantly reduce triglyceride accumulation by downregulating key lipogenic regulators, specifically SREBP-1c and fatty acid synthase (FAS). Beyond its independent effects, CGA offers a strategic clinical advantage; evidence suggests it may enhance metabolic signaling when combined with conventional treatments like metformin, resulting in a more potent, synergistic anti-lipogenic effect (Rubio-Ruiz et al., 2019). This interaction positions the CGA-rich profile of cherry laurel as a high-value candidate for adjunctive therapy in patients struggling with insulin resistance and non-alcoholic fatty liver disease (NAFLD).

Anthocyanins, including cyanidin-3-O-glucoside, further complement these actions through diverse metabolic and endothelial-protective pathways (Oumeddour et al., 2024). These pigments exert anti-atherosclerotic, antihypertensive, and antioxidant effects that support the maintenance of body weight and improved lipid profiles. At the molecular level, anthocyanins decrease lipogenesis while simultaneously increasing fatty acid oxidation by activating the AMPK pathway and stimulating mitochondrial biogenesis. They also modulate PI3K–Akt and GLUT1/4 signaling to enhance insulin sensitivity, inhibit NF- κ B to reduce systemic inflammation, and promote a favorable M1 to M2 macrophage polarization (Godyla-Jabłoński et al., 2024; Oumeddour et al., 2024). Furthermore, experimental studies demonstrate that anthocyanins improve metabolic syndrome through gut microbiota modulation and increased short-chain fatty acid production (Du et al., 2025).

Quercetin, in particular, has demonstrated the ability to significantly improve adiposity, dyslipidemia, and glucose intolerance. In rodent models, it produces coordinated transcriptomic changes in hepatic and adipose tissues, directly enhancing insulin sensitivity. Its systemic impact includes the reduction of epididymal and retroperitoneal fat, lower serum and hepatic triglycerides, and improved fasting insulin levels (Kabelova et al., 2022). Beyond these direct metabolic effects, quercetin also improves antioxidant defenses and reduces hepatic steatosis (Rubio-Ruiz et al., 2019).

Similarly, kaempferol contributes to body weight reduction and improved glycemic parameters primarily by targeting the central nervous system. By suppressing hypothalamic inflammation and altering central energy balance signaling, kaempferol decreases microglial activation in the arcuate nucleus. This central administration leads to marked weight loss, reduced feed efficiency and improved metabolic outcomes (Romero-Juarez et al., 2021).

A critical emerging theme across all compounds is their ability to reshape the gut microbiota and stimulate the production of short-chain fatty acids (SCFAs). For instance, anthocyanin-mediated benefits in high-fat diet models have been linked to the proliferation and increased acetic acid production (Du et al., 2025). These protective phenotypes are so robust that they have proven transferable via fecal microbiota transplantation. Collectively, these flavonoids act as multi-target agents that bridge the gap between gut health, central energy regulation, and peripheral metabolic function, offering a comprehensive pharmacological basis for their use in metabolic syndrome management.

While each flavonoid exhibits unique primary targets—such as quercetin’s focus on hepatic transcriptomic shifts, kaempferol’s regulation of hypothalamic microglial activation, and anthocyanins’ robust activation of mitochondrial biogenesis—they converge on a unified therapeutic front. By collectively modulating the AMPK/PI3K–Akt signaling axes, suppressing NF- κ B-mediated inflammation, and reshaping the gut microbiota to favor short-chain fatty acid production, these compounds offer a sophisticated, multi-level defense against metabolic dysfunction (Godyla-Jabłoński et al., 2024; Oumeddour et al., 2024; Du et al., 2025). This integrated mechanism suggests that a combination of these bioactives, as found naturally in *Prunus laurocerasus*, may provide a more comprehensive intervention than any single isolated compound.

In this context, increasing attention has been directed toward plant-derived sources rich in bioactive compounds (Altuntaş et al., 2018). *Prunus laurocerasus* L. (cherry laurel) represents a promising candidate due to its high polyphenolic content and documented biological activities (Kaya Kartal et al. 2025, Konuk et al. 2024) . The fruit contains significant amounts of flavonoids and various anthocyanins, which are known to exert antioxidant and anti-inflammatory effects (Cai et al., 2004; Djeridane et al., 2006; AbdelRahim and El-Beltagi, 2019). When compared with international datasets (Table 1.) (Halilova et al., 2010; Kaya Kartal et al., 2025; Konuk et al., 2024; Todorova et al., 2025), Our findings suggest that Georgian wild cherry laurel demonstrates strong competitiveness in bioactive compound content.

Aim and Methods

In light of the increasing interest in natural product-based therapeutics, we aimed to investigate the potential benefits of Georgian autochthonous wild cherry laurel (*Prunus laurocerasus*), collected from different locations of western Georgia, in particular, Erge (41°33'41.0"N, 41°41'48.0"E) and Tkhillnari (41°33'49.0"N, 41°39'11.0"E), bioactive compounds in the management of these conditions. We studied the juice of fresh and frozen fruit, the dried product, and, as an additional strategic benefit, the processing residues (skin and pomase). The inclusion of these residues highlights an opportunity for waste valorization; our data reveals that these by-products are not merely industrial waste but are potent carriers of secondary metabolites. This evaluation of

primary fruit products and their processing by-products highlights a sustainable and economically optimized model for pharmaceutical applications.

Regardless of storing, processing method or geographic origin, wild cherry laurel fruit extracts demonstrated a consistently high polyphenolic content, a naturally occurring flavanols with well-documented antioxidant and anti-inflammatory properties that have attracted increasing interest in metabolic disease research. Prior to chemical analysis, we blanched our samples with 80% hot ethanol and then processed it for farther chemical analysis.

Quantitative Determination of Flavonoids

The total flavonoid content was determined using the AlCl_3 spectrophotometric method. One milliliter of the extract was mixed with 5 mL of distilled water and 0.3 mL of 5% NaNO_2 , followed by incubation for 5 minutes. Subsequently, 0.3 mL of 10% AlCl_3 was added, and the mixture was incubated for an additional 6 minutes. Afterward, 2 mL of 1 N NaOH was added. The absorbance of the resulting solution was measured at 510 nm. The results were expressed as milligrams of quercetin equivalents per gram of sample (mg QE/g), using the calibration curve: $y = 1.154x - 0.002$ ($R^2 = 0.999$). (Datuashvili et al., 2025, Abashidze et al., 2024)

Quantitative Determination of Total Anthocyanins

The total anthocyanin content was determined using a rapid direct UV–Vis spectrophotometric method at a wavelength of 520 nm. Sample extraction was performed using 70% ethanol containing 0.1% HCl. The absorbance of the analytical extract was measured at 520 nm (A_{520}) and 700 nm (A_{700}). The corrected absorbance was calculated using the following equation: $A_{\text{corr}} = A_{520} - A_{700}$. The extraction solvent (70% EtOH + 0.1% HCl) was used as a blank. The anthocyanin concentration was calculated based on the Beer–Lambert law: c (mol/L) = $A_{\text{corr}} / (\epsilon \times b)$ where $\epsilon = 26,900 \text{ L} \cdot \text{mol}^{-1} \cdot \text{cm}^{-1}$ and $b = 1 \text{ cm}$. The concentration in mg/L was calculated as: C (mg/L) = $(A_{\text{corr}} \times \text{MW}) / (\epsilon \times b) \times 1000$ where MW (malvidin-3-O-glucoside chloride) = 528.9 g/mol. The results were expressed as milligrams of malvidin-3-O-glucoside equivalents per gram of sample (mg/g) (Giusti et al., 2001)

Determination of Antioxidant Activity by 50% Inhibition of 0.1 mM DPPH Radical (IC_{50})

Antioxidant activity was evaluated using the 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging spectrophotometric assay. Appropriately diluted extracts at different concentrations were mixed with DPPH solution. Specifically, a 1.0 mL aliquot of each extract was combined with 3.0 mL of 0.1 mM DPPH methanolic solution. The reaction mixture was incubated in the dark at room temperature for 30 minutes, after which the decrease in absorbance was measured at 517 nm using a UV–Vis spectrophotometer. The radical scavenging activity was expressed as the percentage of DPPH inhibition ($\text{In}\%$), calculated using the following equation:

$$\text{In}\% = [(A_c - A_s) / A_c] \times 100$$

where A_c is the absorbance of the 0.1 mM DPPH ethanolic solution (control), and A_s is the absorbance of the reaction mixture containing the sample extract. The extract concentration required to achieve 50% inhibition of the DPPH radical (IC_{50}) was calculated using the following equation:

$$\text{IC}_{50} = (m \times V \times F \times 100) / \text{In}\%_{50}$$

where m is the mass of the tested sample (mg), V is the volume of the sample extract (mL), F is the dilution factor, and $\text{In}\%_{50}$ represents the percentage of DPPH inhibition within the 45–55% range used to interpolate the IC_{50} value. The results were expressed as milligrams of sample required to inhibit 50% of the DPPH radical (mg IC_{50}). (Brand-Williams et al., 1995)

Determination of Total Phenolic Content

Total phenolic content was quantified using the Folin–Ciocalteu colorimetric assay. Briefly, 1 mL of the extract was mixed with 1 mL of Folin–Ciocalteu reagent. After a 3-minute reaction period, 1 mL of 10% Na_2CO_3 was

added, and the mixture was diluted to a final volume of 10 mL with distilled water. The reaction mixture was allowed to stand for 90 minutes at room temperature, after which absorbance was measured at 750 nm. The results were expressed as milligrams of chlorogenic acid equivalents per gram of sample (mg/g). (Datuashvili et al., 2024)

Determination of Total Phenolic Acids

Total phenolic acids were determined spectrophotometrically at 320 nm. In brief, 250 μ L of the extract was combined with 250 μ L of 0.1% ethanolic HCl and 4.55 mL of 2% HCl to reach a final volume of 5.05 mL. The mixture was vortexed thoroughly and incubated at room temperature for 15 minutes. Absorbance was then recorded at 320 nm against an appropriate reagent blank. Quantification was performed using a calibration curve, and the results were expressed as milligrams of caffeic acid equivalents per gram of sample (mg/g) (Abashidze et al., 2024)

Results and Discussion

Our analytical results revealed that while Georgian autochthonous *Prunus laurocerasus* (both wild and cultivated) contains a diverse polyphenolic profile (Margalitadze et al., 2024), the concentrations of individual compounds varied significantly among the wild fruit fractions. Chlorogenic acid and anthocyanins were found as the predominant, followed by substantial levels of quercetin. In contrast, kaempferol was identified in comparatively minor concentrations across all samples, regardless of their geographic origin in Georgia. Given this distribution, our investigation into metabolic signaling and therapeutic potential focuses primarily on the dominant bioactive drivers—chlorogenic acid, anthocyanins, and quercetin—which represent the most significant pharmacological components of the our samples of wild cherry laurel extracts. A critical finding of this study is the distribution of these metabolites across the fruit's physical components.

The highest concentrations of bioactive compounds were consistently determined in the pulp, followed by the juice, with the lowest concentrations detected in the processing residues (waste). Specifically, the pulp contained 49.61 mg/g of total phenols and 37.99 mg/g of total flavonoids, nearly doubling the concentrations found in the juice. The same correlation was observed regarding antioxidant activity. The pulp exhibited the most potent radical scavenging capacity (lowest IC_{50}), while the waste fraction showed the lowest activity. However, despite exhibiting lower concentrations relative to the pulp and juice, the wild cherry laurel processing residues still retain appreciable levels of phytochemicals, including 15.75 mg/g of total phenols and 10.24 mg/g of total flavonoids (Chart 1,2,3,4) From a sustainability perspective, these findings underscore the potential of such by-products to function as economically viable raw materials. The retention of significant secondary metabolites in agricultural side-streams supports a circular economy model, allowing for the subsequent extraction and utilization of these compounds in the functional food and pharmaceutical sectors.

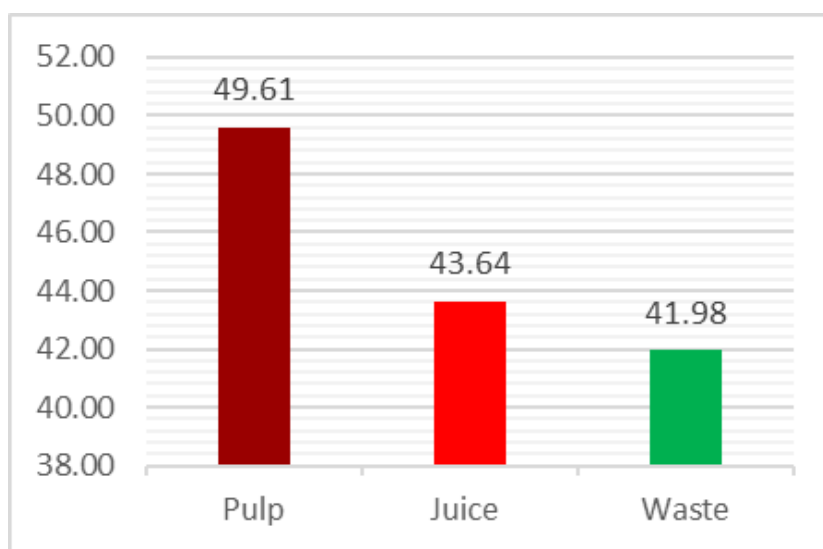


Figure 1. Total phenols of wild cherry laurel (mg/g, as chlorogenic acid equivalents)

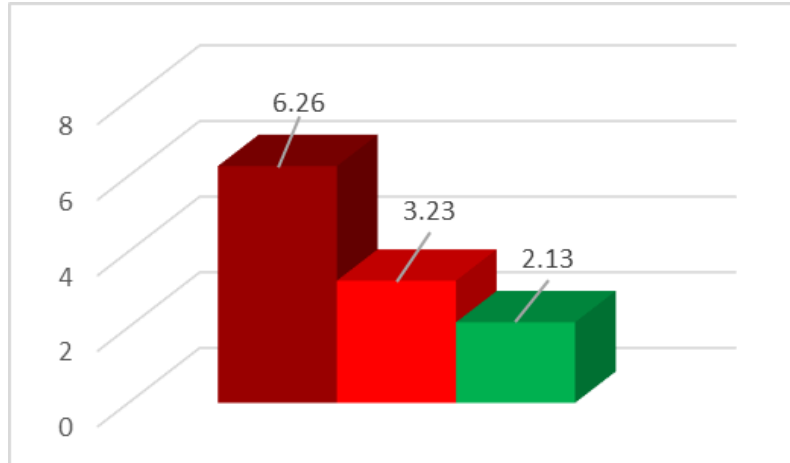


Figure 2. Total anthocyanins of wild cherry laurel (mg/g)

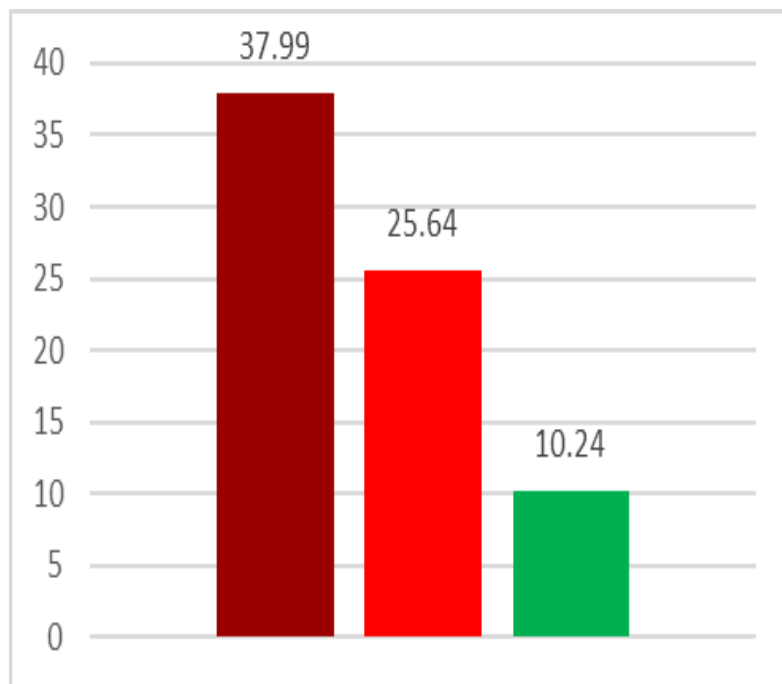


Figure 3. Total flavonoids of wild cherry laurel (mg/g, as quercetin equivalents)

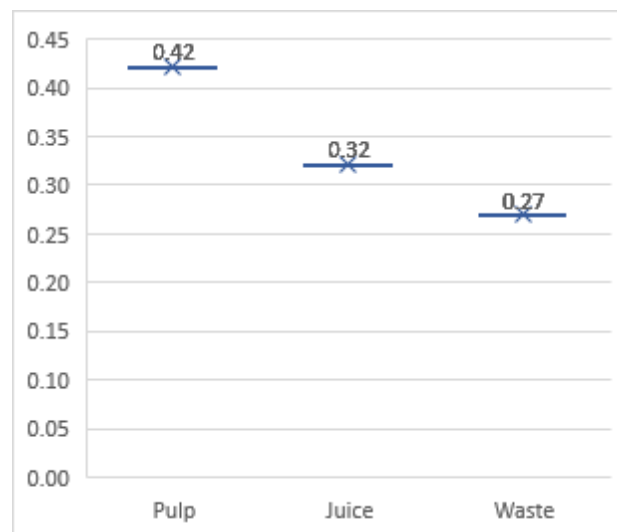


Figure 4. Antioxidant activity (0,1 mM DPPH, IC₅₀ mg of sample)

Table 1. Comparative analysis of bioactive compound levels in Georgian wild cherry laurel versus international literature values

Compound	Georgian wild cherry laurel pulp	International (Avg. numbers from literature)
Total Phenols	49.61 mg/g	15.0 – 40.0 mg/g (DW)
Anthocyanins	6.26 mg/g	0.5 – 2.5 mg/g
Flavonoids	37.99 mg/g	1.0 – 15.0 mg/g

Conclusion

The present study demonstrates that Georgian autochthonous wild cherry laurel (*Prunus laurocerasus*) represents an exceptionally rich and consistent source of bioactive secondary metabolites, specifically chlorogenic acid, anthocyanins, and quercetin. Notably, this phytochemical profile remains stable regardless of the geographic origin within Georgia or the storage method, suggesting the plant's reliability as a high-quality raw material for future therapeutic applications. This unique composition provides a potent "natural cocktail" for multi-target metabolic defense. By collectively modulating critical pathways such as AMPK and PI3K–Akt signaling, and suppressing NF-κB-mediated inflammation, these compounds offer a sophisticated defense against the core pathologies of metabolic syndrome. Our findings suggest that *P. laurocerasus* extracts can provide essential protection against systemic oxidative stress and serve as a valuable adjunctive strategy alongside standard clinical treatments for obesity, insulin resistance, and type 2 diabetes. Furthermore, while the fruit pulp and juice serve as the primary reservoirs for these metabolites, our data reveals that processing residues (waste) retain significant bioactive potency. These residues represent a high-value source for nutraceutical development. By successfully valorizing these agricultural side-streams, this research supports a sustainable circular economy model that reduces environmental impact while providing cost-effective medicinal resources. Collectively, these findings establish a rigorous foundation for the development of specific Georgian-sourced functional foods and pharmaceutical additives aimed at addressing the escalating global epidemic of obesity and metabolic dysfunction.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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Author(s) Information

Eteri Margalitadze

Avicenna Batumi Medical University
Tbeti st. 4, Batumi, Georgia.
Batumi Shota Rustaveli State University, Ninoshvili av. 35
Batumi, Georgia.
ORCID iD: <https://orcid.org/0000-0003-2088-212X>
*Contact e-mail: eter.margalitadze@bsu.edu.ge

Nona Surmanidze

Batumi Shota Rustaveli State University
Ninoshvili av. 35, Batumi, Georgia.
ORCID iD: <https://orcid.org/0000-0002-9044-9121>

Indira Japaridze

Batumi Shota Rustaveli State University
Ninoshvili av. 35, Batumi, Georgia
ORCID iD: <https://orcid.org/0000-0003-2088-212X>

Maia Vanidze

Batumi Shota Rustaveli State University
Ninoshvili av. 35, Batumi, Georgia
ORCID iD: <https://orcid.org/0000-0003-0807-0735>

Aleko Kalandia

Batumi Shota Rustaveli State University
Ninoshvili av. 35, Batumi, Georgia
ORCID iD: <https://orcid.org/0000-0001-9570-9263>

*Corresponding author(s) contact email

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Synthesis of Titanium-Containing Coatings in Aqueous-Organic Electrolytes

Olga Popova

Don State Technical University

Larisa Pustovaya

Don State Technical University

Besarion Meskhi

Don State Technical University

Abstract: The conditions and results of low-temperature electrochemical synthesis, allowing for the targeted production of phases of a given composition on the titanium surface, are considered. Functional coatings were obtained on thin ($10\div 15\ \mu\text{m}$) titanium layers in the potentiostatic mode at potential values of $4\div 10\ \text{V}$ and a maximum current of no more than $0.02\ \text{A}$ in aqueous-organic electrolytes based on ethylene glycol, in the presence of additives of various salts in the concentration range from 0.05 to $0.5\ \text{wt. \%}$. As a result of electrochemical treatment of the titanium surface in electrolytes, solid electrically conductive films with a mirror surface from light yellow to bronze shades are formed. The microhardness of the coatings, measured by the Vickers method, is at least $946\ \text{HV}\ 0.1$, which indicates the high mechanical strength of the materials. The specific resistance of the coatings does not exceed $2.1\ \text{Ohm}\cdot\text{cm}$. X-ray photoelectron spectroscopy studies of the elemental composition and chemical states of the resulting coatings reveal the presence of titanium, oxygen, carbon, and nitrogen on the sample surfaces, with oxygen primarily present in the upper oxidized layer. Coatings obtained in all studied electrolytes contain the $\text{Ti}(\text{C}_x\text{N}_y)$ phase and oxide phases (TiO , Ti_2O_3 , TiO_2).

Keywords: Electrochemical modification of titanium, X-ray photoelectron spectroscopy, Chronoamperograms, Phase composition, Titanium carbonitride.

Introduction

The importance of titanium and its alloys to modern industry is difficult to overestimate. Its unique physical, chemical, and mechanical properties determine its widespread use in virtually all industries. Surface modification techniques for titanium and its alloys allow for targeted modification of their properties, enhancing their performance characteristics. Surface oxidation is most commonly used through electrochemical, plasma-electrolytic, or microarc oxidation. This allows for the production of biocompatible implant materials with a porous coating that mimics bone structure, accelerating the process of osseointegration. It has been shown that the morphology, thickness, crystallinity, chemical composition, mechanical properties, corrosion resistance, and bioactivity of coatings are highly dependent on the parameters of electrochemical processes (voltage, process duration, electrolyte composition and temperature, etc.) (Makurat-Kasprolewicz & Ossowska, 2023; Brocklebank et al., 2022; Huang & Yoshimura, 2023; Gangqiang Li et al., 2023).

Titanium nitride films are also widely used, having proven themselves as decorative coatings, coatings for friction surfaces, and functional layers in microelectronics, increasing their wear resistance, reliability, and durability.

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Furthermore, Ti_xN_y compounds exhibit good conductivity, high hardness, chemical and temperature stability, and are resistant to aging processes (Maryeva & Popova, 2016; Brover et al., 2023).

Titanium carbide-containing coatings can increase hardness and corrosion resistance and reduce the friction coefficient of cutting and milling tools. The structure and mechanical properties of TiC_x films also depend on the synthesis parameters (Sumanya et al., 2023). Most often, titanium carbide films are obtained by plasma spraying or magnetron sputtering. It has been established that an optimized x value is a key factor in improving the performance characteristics of TiC_x films used under extreme wear conditions (Xie et al., 2023; Abegunde et al., 2021; Tamarkin et al., 2023). The combination of several types of alloying additives in the coating composition makes it possible to vary their properties depending on the technical tasks and operating conditions of the final product. For example, a TiO_2 - TiN composite coating has been created, which has significant potential for the creation of surface structures of vascular stents (Xin Chen et al., 2023). The authors of Xiao Chen et al. (2023) succeeded in combining the good mechanical properties of TiN film (surface hardness, elastic modulus, cytocompatibility) with the excellent anticoagulant properties of TiO_2 . Coating implants with films of TiO_2 - TiC_x composition also showed good results (Veronesi et al., 2017).

In a study (Jie Jin et al., 2021), the continuous field unbalanced ion sputtering (CFUMSIP) technology was used to produce $TiCN$ coatings with high electrical conductivity and excellent corrosion resistance by simultaneously feeding acetylene (C_2H_2) and nitrogen (N_2) into the chamber. The resulting TiN - $TiCN$ -based coatings were proposed for use in membranes in fuel cells. Titanium carbonitride films also exhibit electrocatalytic properties (Gujral et al, 2022; Roca-Ayats et al, 2020), as well as outstanding specific capacitance, low internal resistance, and high cyclic stability, making them promising for the fabrication of symmetrical supercapacitors (Iffat Ashraf et al., 2023).

Each of the above coatings has its own advantages and disadvantages. Improving performance characteristics and reducing resource and energy consumption during the coating application process remains a pressing issue. A synergistic effect is expected from creating composite coatings while maintaining environmental and economic efficiency. The aim of this work is to establish the relationship between the synthesis conditions and the properties of multicomponent titanium carbonitride-containing coatings obtained using environmentally friendly soft chemistry methods.

Method

Electrochemical Syntheses

Electrochemical syntheses were carried out in potentiostatic mode using a P-30I potentiostat at ambient temperature (approximately 20°C). The electrolyte base for the syntheses was ethylene glycol (EG) with the addition of 10% water. Electrically conductive additives included ammonium, sodium, potassium, and lithium fluorides, as well as $LiClO_4$, NH_4SCN , and other compounds. The anodes were titanium plates with a surface area of 2–2.5 cm^2 , which were fabricated by thermal spraying of titanium layers (99.99% purity) onto glass-ceramic substrates with a thickness of ~15 μm . A titanium plate with an area of 2 cm^2 served as an auxiliary electrode. Before each synthesis, the electrodes were cleaned using cathode-anodic polarization. The end time of the synthesis was determined from the $I-t$ dependence, when the current became zero. The studied samples were obtained at potentials of 4 ÷ 10 V relative to (Ag/AgCl, KCl(sat)). The electrical conductivity of electrolyte solutions was measured using an OK-102/1 conductometer (Radelkis).

Microstructure and Properties of Coatings

Micrographs of the samples were obtained using a Quanta 200 scanning electron probe microscope. To determine the microhardness of the titanium nitride layers, a method established in accordance with GOST 9450-76 was used. This method requires the use of a PMT-3 microhardness tester and involves indenting a square diamond tip into the sample under a load of 0.981 N for 10-15 seconds, followed by analysis of the recovered indentation. The specific resistance of the samples was determined using the four-probe method.

Elemental and Phase Composition of Coatings

Analysis of the elemental composition and chemical states of atoms was performed for samples synthesized in electrolytes of the following composition:

- 1 – (EG + 10% H₂O + 0.5% NH₄SCN);
- 2 – (EG + 10% H₂O + 0.5% LiF);
- 3 – (EG + 10% H₂O + 0.5% LiClO₄);
- 4 – (EG + 10% H₂O + 0.25% NH₄F).

The elemental composition of the coatings was studied by X-ray photoelectron spectroscopy (XPS) on a K-Alpha spectrometer (Termo Scientific) with an AlK_α X-ray source (1486.6 eV). During the measurements, the pressure in the analyzer chamber did not exceed 2.3×10^{-9} mbar. When analyzing the photoelectron spectra, secondary electron background subtraction was performed using the Shirley method. To compensate for the shift of photoelectron lines due to possible charge accumulation on the surface, a compensating gun was used during measurements. The binding energies of the lines were calibrated using the position of the component corresponding to the sp²-hybridized carbon state with a binding energy of 284.8 eV (C_{1s}). To analyze the ratios of coating components in different chemical states, the Gauss-Maxwell peak decomposition method was used. The spectrometer was calibrated using the following lines: Au 4f_{7/2}–83.96 eV, Cu 2p_{3/2}–932.62 eV and Ag 3d_{5/2}–368.21 eV.

Immediately prior to spectroscopic studies of the composition and chemical states of the coatings, the surface was cleaned of any contaminating layer by bombardment with argon ions (as a rule, titanium nitride films synthesized by the electrochemical method are coated with an oxide layer on top). Potential shifts due to residual charge were monitored using the position of the sp²-hybridized carbon peak with a binding energy of 284.8 eV, which is part of the residual surface contamination.

To describe the titanium peak in the metallic state, the LA (1,1.5,7) function with its characteristic asymmetry (Biesinger et al., 2010) was used, and to describe the remaining chemical states, the Voigt GL(30) function in the CASAXPS program was used.

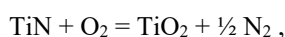
Results and Discussion

Features of Electrochemical Modification of Titanium in Various Electrolytes

During the electrochemical modification of titanium in electrolytes with NH₄F as a conductive additive, a relationship is observed between the NH₄F concentration and the nature of the resulting products. In particular, the formation of predominantly titanium carbides and nitrides or titanium oxide is possible. In ethylene glycol with an NH₄F concentration in the range of 0.05 ÷ 0.25 wt. % and a corresponding electrolyte conductivity of $0.2 \cdot 10^{-3} \div 0.7 \cdot 10^{-3}$ S/cm, the formation of titanium carbonitrides was observed in the potential range of 2 ÷ 14 V (Maryeva & Popova, 2016). A characteristic chronoamperogram for this process (curve 1) is shown in Figure 1 in comparison with the chronoamperogram corresponding to the formation of TiO₂ at an NH₄F concentration of 0.5 wt.% (curve 2).

Electrochemical modification of titanium in the absence of nitrogen-containing electrolytes also results in the formation of titanium carbides and nitrides. The increase in oxidation potential is visually accompanied by a change in the surface color of the modified layers. The chronoamperograms of processes occurring at different anode potentials differ in nature. In the curves corresponding to potentials in the range of 3–6 V (Figure 2, a), the current density decreases steadily. In contrast, in the chronoamperograms of processes occurring at anode potentials of 7–10 V (Figure 2, b), the current density initially decreases and then, after 30–50 seconds, slowly increases.

Presumably, at higher synthesis potentials (and hence higher initial current values) in the presence of fluorides, the formed Ti(CXNY) is subject to destruction as a result of, for example, an oxidation reaction leading to the formation of titanium oxide (Maryeva & Popova, 2016):



The calculated Gibbs energy change for this reaction is –582.2 kJ/mol.

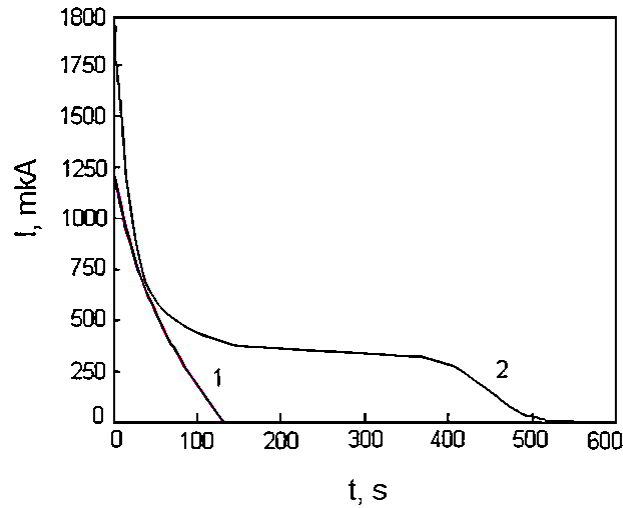


Figure 1. Chronoamperograms at an anode potential of 4 V: 1 – the process of $\text{Ti}(\text{C}_x\text{N}_y)$ formation in the electrolyte EG– H_2O – NH_4F (89.8–10.0–0.2 wt.%); 2 – the process of TiO_2 formation in the electrolyte EG– H_2O – NH_4F (89.5–10.0–0.5 wt.%)

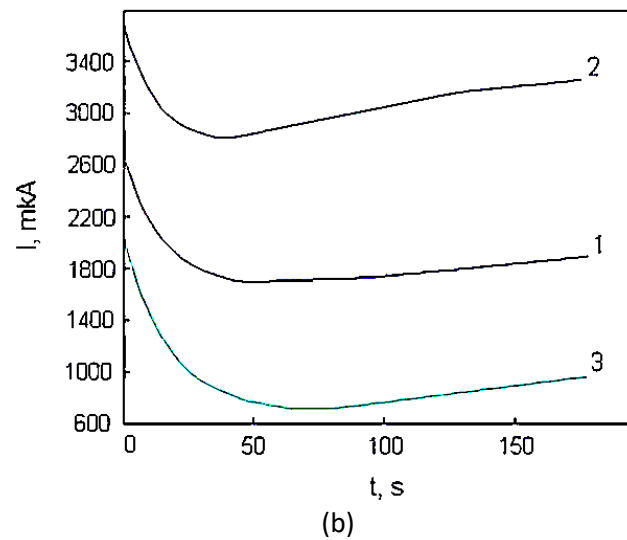
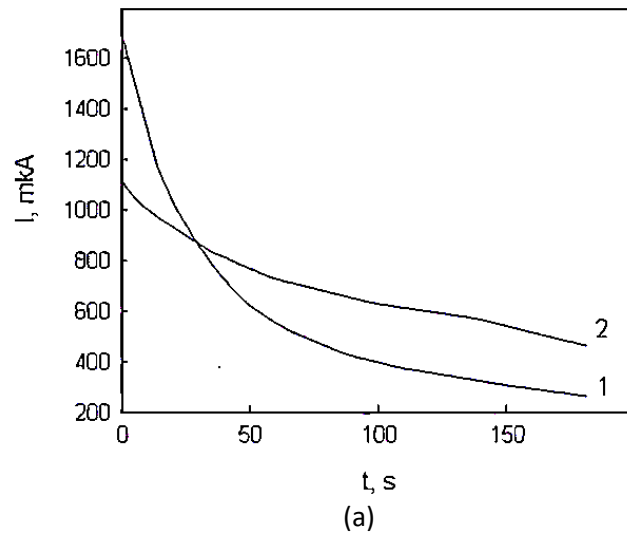


Figure 2. Chronoamperograms of processes at potentials of 4 V – (1a); 6 V – (2a); 8 V – (1b); 10 V – (2b) in the electrolyte (EG + 10% H_2O + 0.27 mol/l KF); at a potential of 10 V – (3b) in the electrolyte (EG + 10% H_2O + 0.27 mol/l LiF)

Study of Microstructure and Properties of Coatings

Electrochemical processing of titanium layers in these electrolytes produces conductive coatings with a wide range of color shades, from light yellow to bronze. Films of samples 1–3 are characterized by the formation of an almost homogeneous layer with a mirror surface, practically free of defects. These films adhere tightly to the base substrate and precisely replicate its microrelief (Figure 3, a). The layer from sample 4 (conductive additive NH_4F) exhibits structural unevenness due to the distinct presence of various phases (Figure 3, b). The microhardness of the coatings from samples 1–3, measured using the Vickers method, is at least 946 HV 0.1, indicating the high mechanical strength of these materials. The specific resistance of the films does not exceed 2.1 Ohm·cm.

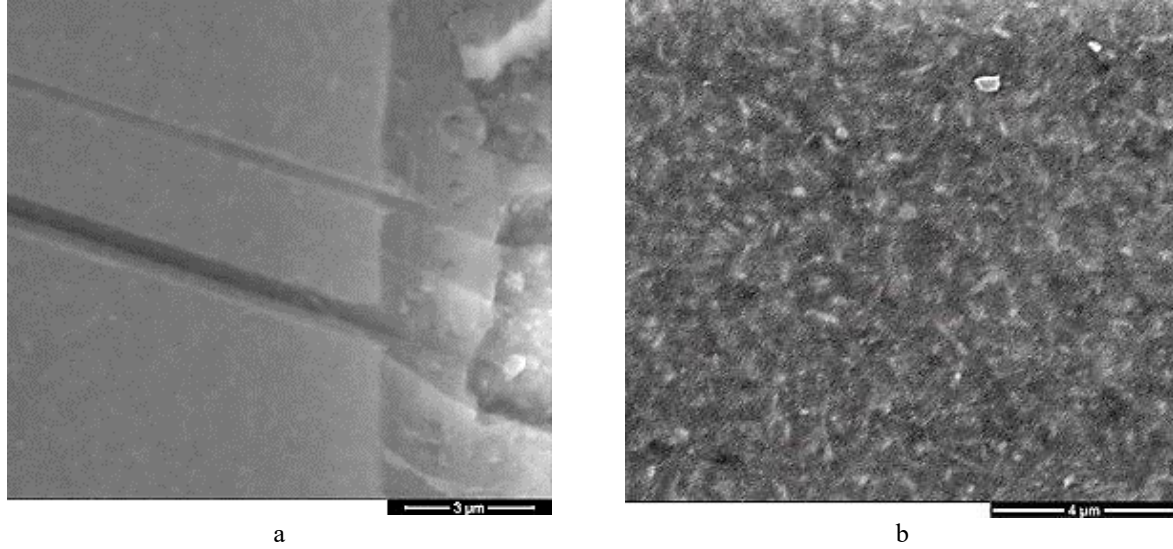


Figure 3. Microstructure of the surface of the synthesized coating at a potential of 6 V ($\times 20000$): (a) in the EG– H_2O – LiClO_4 electrolyte (89.5–10–0.5 wt.%); (b) in the EG– H_2O – NH_4F electrolyte (89.75–10.0–0.25 wt.%)

Analysis of the Elemental Composition and Chemical States of Atoms of the Synthesized Coatings

Below are the results of XPS analysis for the surface of sample 1, obtained in an electrolyte of the composition EG+ H_2O + NH_4SCN (89.5–10.0–0.5 wt.%). The overview spectrum shows the presence of mainly titanium, oxygen, carbon, and nitrogen on the surface (Figure 4, Table 1), with the amount of oxygen being much greater than the other components, indicating the presence of an oxidized layer.

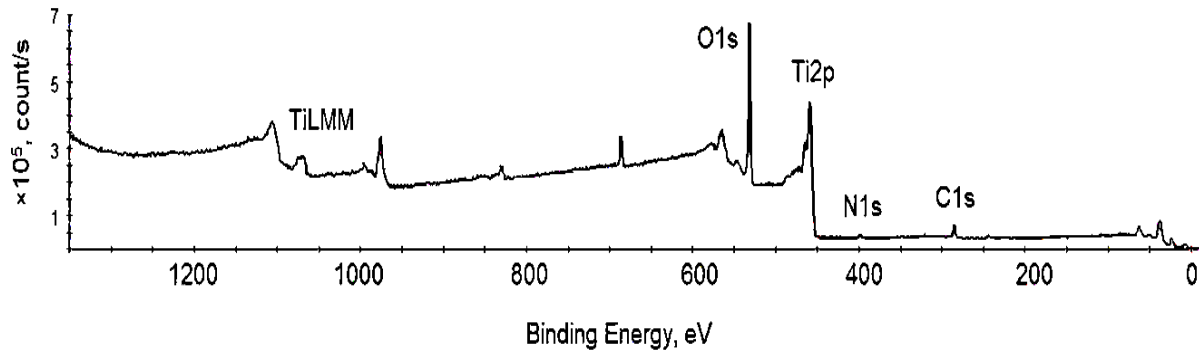


Figure 4. Survey spectrum of the surface of sample 1

Table 1. Chemical composition of the surface of sample 1

Lines of elements	O	Ti	C	F	N
Content of elements, at. %	46,22	20,33	12,29	8,99	3,06

The chemical states of the components on the surface of sample 1 were analyzed by decomposing the photoelectron peaks into their components. The obtained data are in good agreement with studies of TiCN using XPS (Miller et al., 2012; Xin Feng & Li-Yi Shi, 2005).

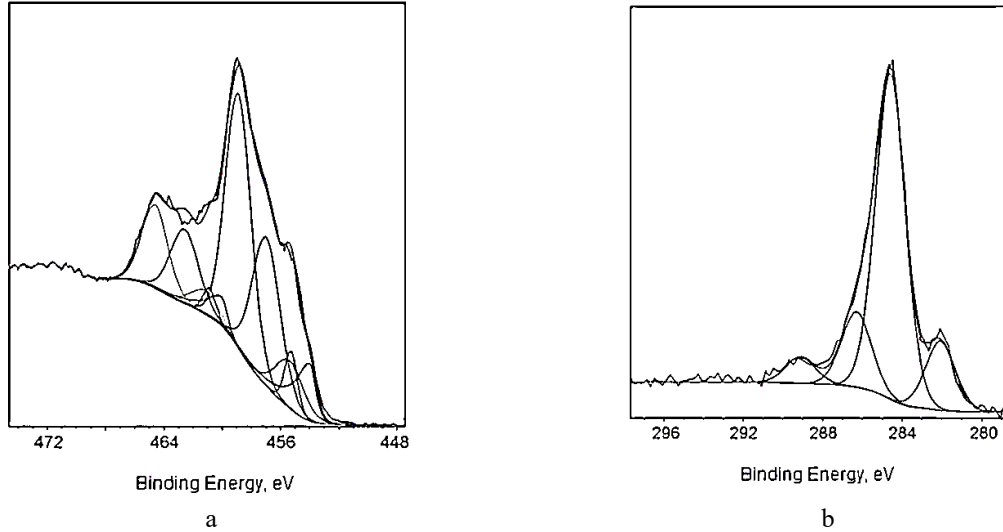


Figure 5. Analysis of chemical states: spectrum of titanium Ti 2p (a) and carbon C 1s (b) on the surface of sample 1

Figure 5a shows the decomposition results for the peak of the titanium Ti 2p doublet. The small amount of metallic titanium present on the surface, which was probably formed as a result of cleaning the sample surface by bombardment with argon ions, is 10.85 at.%. This state of titanium Ti 2p_{3/2} corresponds to a binding energy of 454.0 eV. Titanium with oxygen forms the following states: Ti II (455.41 eV – 9.99 at.%), Ti III (457.0 eV – 30.78 at. %), and Ti IV (458.9 eV – 43.03 at. %). The state of titanium with carbon and nitrogen corresponds to the compound TiCN (455.3 eV – 5.35 at. %).

Carbon atoms are primarily present in the residual contaminant layer on the surface, which corresponds to a binding energy of 284.5 eV. According to the spectrum and the results of chemical state analysis in the region of the C 1s line (Figure 5b), this peak remains the most intense even after surface cleaning. Furthermore, a carbon peak at 282.08 eV is clearly visible, corresponding to the Ti–CN bond (13.87 at. % of the total carbon on the surface). Carbon in the C–O/C–N and C=O states, which are part of the contaminant layer, corresponds to binding energies of 286.3 and 289.1 eV. Nitrogen forms the compounds C–N (400.26 eV – 17.04 at.%), N–O (400.26 eV – 17.04 at.%), and Ti–CN (396.8 eV – 57.74 at.%) (Figure 6, a) (Miller et al., 2012). The oxygen spectrum (Figure 6, b) is represented by the states: lattice oxygen Ti–O (530.5 eV – 75.88 at.%), N–O (531.84 eV – 17.6 at.%), C–O (533.3 eV – 6.52 at.%) (Miller et al., 2012). The results of the study of the stoichiometry of the phase composition of the obtained coatings are presented in Table 2.

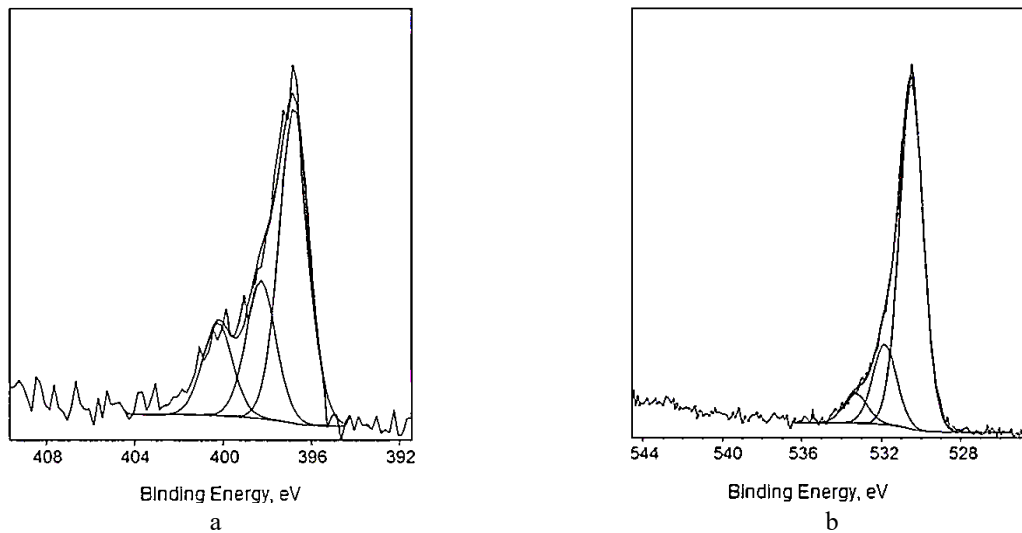


Figure 6. Analysis of chemical states: spectrum of nitrogen N 1s (a) and spectrum of oxygen O 1s (b) on the surface of sample 1

Table 2. Stoichiometric composition of $Ti(C_xN_y)$ phases obtained in different electrolytes

Components	at. %	(C+N)/Ti	$Ti(C_xN_{1-x})$
Sample 1: Electrolyte (EG + 10% H ₂ O + 0,5% NH ₄ SCN)			
Ti	65,73		
C	27,43	0,52	$Ti(C_{0,8}N_{0,2})$
N	6,84		
Sample 2: Electrolyte (EG + 10% H ₂ O + 0,5% LiF)			
Ti	76,67		
C	16,7	0,3	$Ti(C_{0,74}N_{0,26})$
N	6,63		
Sample 3: Electrolyte (EG + 10% H ₂ O + 0,5% LiClO ₄)			
Ti	79,03		
C	14,53	0,26	$Ti(C_{0,69}N_{0,31})$
N	6,44		
Sample 4: Electrolyte (EG + 10% H ₂ O + 0,5% NH ₄ F)			
Ti	82,21		
C	11,88	0,21	$Ti(C_{0,66}N_{0,34})$
N	5,91		

X-ray photoelectron spectroscopy analysis of the composition and chemical states of the samples revealed that the $Ti(C_xN_y)$ phase was present in all four samples. The highest content of this phase was found in sample 1 (NH₄F, an electrically conductive additive). In the other three samples, the $Ti(C_xN_y)$ phase content was significantly lower, and oxide phases (TiO, Ti₂O₃, TiO₂) played a significant role.

Conclusion

During electrochemical modification at low potentials (4–10 V) and a maximum current of no more than 0.02 A in water-containing ethylene glycol in the presence of various conductive additives, titanium carbonitride and oxide phases are formed. The composition of the resulting products varies depending on the conductive additive and the potential during synthesis. Titanium oxide formation is characteristic in the presence of ammonium fluoride and largely depends on its concentration. In the presence of Li, Na, and K fluorides, titanium oxide formation begins at potentials of 8–10 V. Coatings formed in electrolytes with the other conductive additives studied are primarily composed of titanium nitrides and carbides. The stoichiometric composition of the $Ti(C_xN_y)$ phases in the resulting coatings was determined.

Scientific Ethics Declaration

* The authors declare that the scientific, ethical, and legal responsibility of this article, published in the EPSTEM journal, belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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Author(s) Information

Olga Popova

Don State Technical University
Gagarin square 1, Rostov-on-Don, 344000, Russia
ORCID iD: <https://orcid.org/0000-0002-8130-61964>
*Contact e-mail: olyp2808@rambler.ru

Larisa Pustovaya

Don State Technical University
Gagarin square 1, Rostov-on-Don, 344000, Russia
ORCID iD: <https://orcid.org/0000-0002-3146-9819>

Besarion Meskhi

Don State Technical University
Gagarin square 1, Rostov-on-Don, 344000, Russia
ORCID iD: <https://orcid.org/0000-0003-3497-3102>

*Corresponding author(s) contact email

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Green Hydrogen Production by Photovoltaic Energy

Zeyneb Charki

University of Bechar - Tahri Mohamed

Samira Bediar

University of Bechar - Tahri Mohamed

Hachemi Glaoui

University of Bechar - Tahri Mohamed

Rachid Dehini

University of Bechar - Tahri Mohamed

Abstract: This paper presents a comprehensive MATLAB-based simulation study of hydrogen production powered by photovoltaic (PV) energy systems. The proposed model integrates several key subsystems including solar irradiance modeling, photovoltaic array electrical characteristics, electrolyzer operation, hydrogen production rate estimation, and overall system efficiency evaluation from PV generation to hydrogen output (PV-to-H₂). The simulation framework allows the analysis of the dynamic behavior of the system under varying environmental conditions such as solar radiation and temperature. Particular attention is given to the performance of the electrolyzer and its interaction with the PV power source. In addition, the hydrogen flow rate and energy conversion efficiency are evaluated to assess the technical feasibility of the system. An economic analysis is also conducted using the Levelized Cost of Hydrogen (LCOH) as a key indicator for estimating the cost competitiveness of the proposed solution. The simulation results are carefully validated and compared across different operating scenarios reported in previous studies, showing good agreement and demonstrating the reliability of the developed MATLAB model. The proposed approach provides a useful tool for evaluating and optimizing renewable-based hydrogen production systems, particularly in regions with high solar potential such as Southern Algeria.

Keywords: Photovoltaic, Electrolyzer, Hydrogen, Simulation, Efficiency, LCOH, Renewable energy

Introduction

Clean & green ways to make power have been looked for. This is due to the world's lean to a low-carbon world. One such good fix is green gas. It is made by splitting water with power from green ways. Thus, it supports decarbonization goals and establishes the energy vector as scalable and emission-free. Since photovoltaic energy converts solar energy into electricity in an abundant manner (Ball & Wietschel, 2009), it is environmentally friendly and easily integrated with electrolysis systems. That is why coupling PV systems and water electrolyzers enables hydrogen generation from totally renewable sources with minimum carbon footprint (IEA, 2019).

This paper treats the simulation of the stand-alone PV-electrolyzer system and performance assessment of its green hydrogen production (Acar & Dincer, 2015). The study involves dynamic solar irradiance simulation, solar power generation simulation, and electrolyzer efficiency simulation by considering the influence of environmental parameters such as temperature and sunlight intensity. Key electrical parameters such as voltage,

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current, and power are studied at varying conditions to determine the behavior of the system. Besides, the economic feasibility of the system is carried out by taking into account the LCOH, in order to assess its cost efficiency in the long term (Acar & Dincer, 2014). From the simulation results under various operational conditions, invaluable insights are acquired on the practical implementation of PV-powered hydrogen systems (Kougias, I., & Szabó, S. (2017)).

System Description

In this set up, a lone PV unit links right to a PEM unit. The PV unit gets sun light & turns it to power. This power drives the split of water into gas—hydro and oxy. This set up is spread out & good for the earth. It makes hydro by use of sun light, with no help from old fuel. The build is kept straight. There is no store unit or DC/DC change. So, power goes right from the PV to the PEM unit (Choudhary et al., 2021).

The PEM unit is picked for its quick act, high work rate, & fit for up-&-down power as sun units. The build lets hydro be made each night. So, real checks of how it works under change in sun & heat can be done. This build fits well for far or off-grid spots where grid use is low or not there & where there is a strong wish to use clean power on its own (Buttler & Spliethoff, 2018).

Photovoltaic Model

The solar (PV) part is made with the one-diode same part plan. It hits a mix of true show & easy math use. This build gets the odd ways of the sun cells by looking at big things like sun rays & cell heat. The flow out of the PV part is set by the following expression:

$$I_{PV} = I_{ph} - I_0 \left[\exp \left(\frac{q(V_{PV} + I_{PV}R_s)}{nkT} \right) - 1 \right] - \frac{V_{PV} + I_{PV}R_s}{R_{sh}} \quad (1)$$

Where:

- I_{ph} is the photo-generated current,
- I_0 is the diode saturation current,
- R_s and R_{sh} are the series and shunt resistances, respectively,
- q is the elementary charge,
- n is the diode ideality factor,
- k is Boltzmann's constant,
- T is the cell temperature in Kelvin,
- V_{PV} and I_{PV} represent the output voltage and current.

The PV set-up ran in MATLAB/Simulink. It used things like sun light, air temp, & panel specs. The out notes—power, volts, & flow—are all tracked non-stop. They match the change in work states. These out notes help check the power that goes to the cell in real time. This means we can track how the system does all day.

Electrolyzer Model

The device uses key base rules of electrochem. It uses Faraday's well-known laws too. It turns the power from the sun cells into chem force. It does this by breaking water into hydrogen & oxygen gas. The hydrogen

production rate $\left(\dot{n}_{H_2} \right)$ is determined using the following relation (Zeng & Zhang, 2010):

$$\dot{n}_{H_2} = \frac{\eta_{EL} \cdot P_{EL}}{HHV \cdot F \cdot z} \quad (2)$$

Where:

- η_{EL} is the electrolyzer efficiency,
- P_{EL} is the electrical power input,
- HHV is the higher heating value of hydrogen,
- F is the Faraday constant,
- z is the number of electrons required to produce one mole of hydrogen (typically $z = 2$).

This model accounts for the thermal and electrical behavior of the electrolyzer, including variations in efficiency due to current density and temperature. Losses such as heat dissipation and overpotential are also considered to improve the accuracy of the simulation (Harrouz & Glaoui, 2022).

The electrolyzer operates under a direct coupling configuration with the PV array, enabling real-time hydrogen generation that closely follows the available solar power. This direct integration simplifies the system design while allowing dynamic performance evaluation under fluctuating environmental conditions (Ghenai & Janajreh, 2020).

Methodology

This section presents the adopted modeling strategy, simulation framework, and economic analysis conducted to evaluate the performance and feasibility of the integrated PV-electrolyzer hydrogen production system.

Solar Irradiance Profile

A synthetic irradiance profile was developed in a manner to introduce the concept of variability concerning solar input through the day. The profile ranges from 0 to 1000 W/m² and contains the nature of daily fluctuations in solar intensity-gradually building up from that of the early morning, hitting the peak around noon, and gradually diminishing by the late afternoon. This profile acts as an important input parameter for the PV model, thereby affecting the power output and finally the hydrogen production rate.

Simulation Parameters

The system was simulated using MATLAB/Simulink with a one-minute time resolution over a full 24-hour cycle. Several key parameters were incorporated into the model:

- *PV Array Specifications:* Number of panels, efficiency, and electrical characteristics
- *Electrolyzer Parameters:* Efficiency, operating voltage range
- *Ambient Temperature:* Either constant or variable based on a predefined profile
- *Load Matching Conditions:* Direct coupling between the PV system and electrolyzer without implementing maximum power point tracking (MPPT)

The PV unit sends power right to the electrolyzer. The live link between the two lets it work out hydrogen on the fly. This mimics a true off-grid set-up. There's no store in the mid or DC-DC change.

Economic Evaluation

We looked at how well the system did. We used the Levelized Cost of Hydrogen (LCOH). It tells us the cost per kilogram of hydrogen. The cost is for the whole life of the system. The LCOH helps us see this cost.

The LCOH is calculated using the following equation:

$$LCOH = \frac{C_{cap} + \sum_{t=1}^N \frac{CO\&M(t)}{(1+r)^t}}{\sum_{t=1}^N \frac{H_{prod}(t)}{(1+r)^t}}$$

Where:

- C_{cap} : Initial capital cost of the PV and electrolyzer systems
- $CO\&M(t)$: Operating and maintenance cost in year t
- $H_{prod}(t)$: Annual hydrogen production in year t
- r : Discount rate
- N : Project lifetime in years
- Economic input data were sourced from recent market studies and literature to ensure a realistic and up-to-date financial analysis of the proposed system

Results and Discussion

In this section, the more in-depth analyses of the results of the integrated PV-electrolyzer system with changing environmental conditions have been carried out. The simulation was done over a 24-hour-only diurnal cycle to observe the dynamic behavior of solar irradiance, electrical characteristics, hydrogen production rates, system efficiency, and economic viability. The following plots describe performance characteristics under the presence or absence of cloudeeniness in the sky.

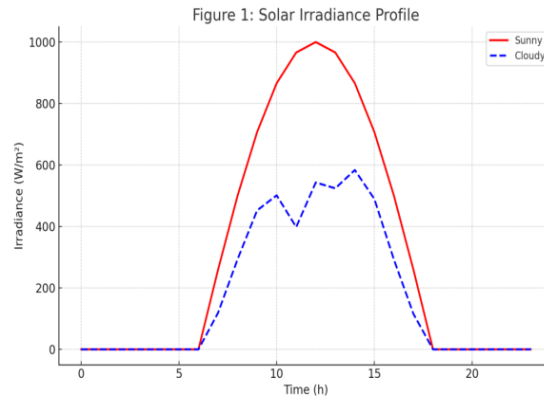


Figure1. Daily solar irradiance profile under sunny and cloudy conditions. The irradiance peaks at midday and drops toward the evening, showing a clear contrast between weather conditions.

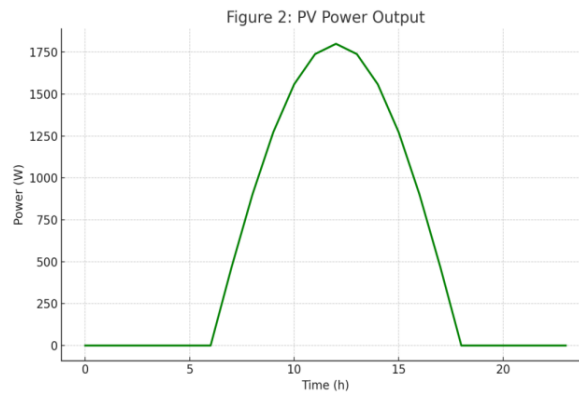


Figure 2. Electrical power generated by the PV array. The maximum power output aligns with the irradiance peak, confirming model reliability.

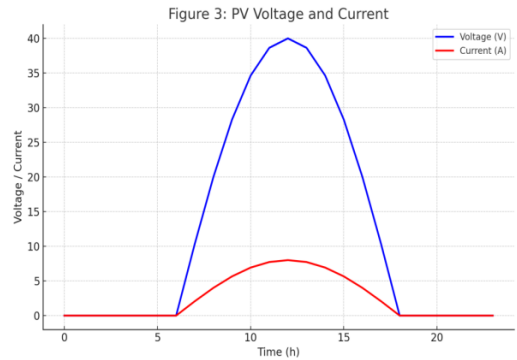


Figure 3. PV module output voltage and current as a function of time. Voltage remains relatively stable, while current follows the irradiance profile

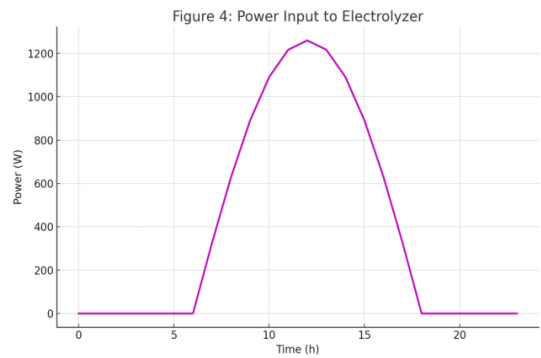


Figure 4. Power delivered to the electrolyzer during the day. The power input closely mirrors PV output dynamics.

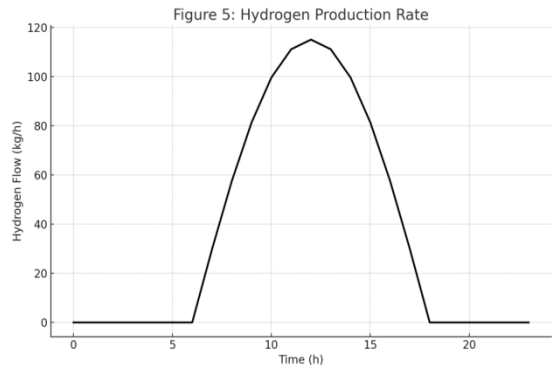


Figure 5. Hourly hydrogen production rate derived from electrolyzer input power. The trend highlights the direct dependence on solar energy availability

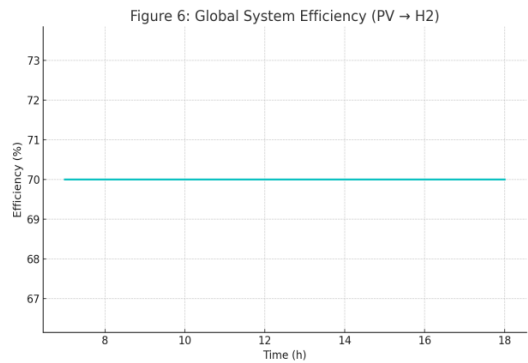


Figure 6. Global energy conversion efficiency from PV to hydrogen. Efficiency remains stable with slight variations due to irradiance and temperature

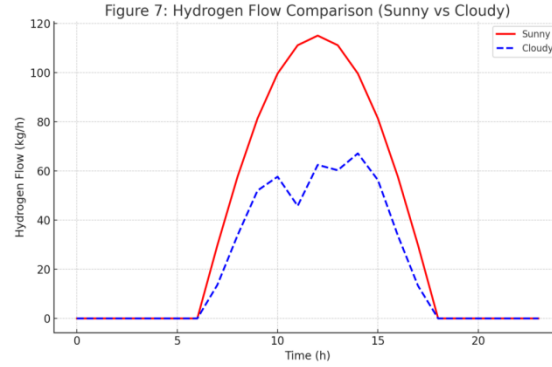


Figure 7. Hydrogen production rate comparison between sunny and cloudy scenarios. Significant reduction is observed under cloudy conditions

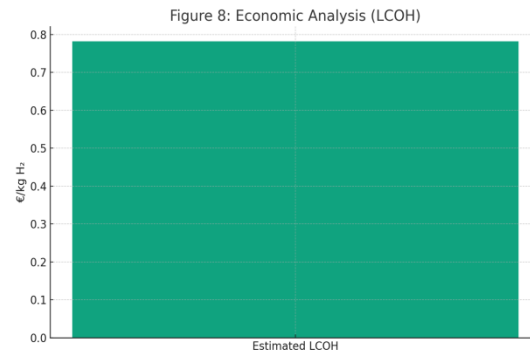


Figure 8. Levelized Cost of Hydrogen (LCOH) illustrating the estimated economic viability of the system based on operational and capital expenditures

The figure 1 shows the solar irradiance profile over a 24 hour period integrated over the day for sunny and cloudy case. The sunny case shows a clear sytem peaks at 1000 W/m² at noon, while the cloudy case shows more irregularities and lower overall irradiance. The variation serves as the primary input to the PV system and it influences all downstream energy and hydrogen generation processes. The electrical power output for the PV array is shown in figure 2. The power generated mirrors the irradiance curve, as expected. The generated power reaches a peak during midday under sunny conditions, which demonstrates the PV model's effectiveness in capturing solar energy and dynamics. The coorelation between irradiance and power output ascertains the PV system's real time adaptability³⁰. The PV array's voltage and current profiles appear in figure 3. Voltage is fairly constant throughout the day. The current however shows a bell shaped profile aligned to the solar irradiance. This electrical behavior verifies that the PV output is appropriate for direct coupling with the electrolyzer. The power supplied to electrolyzer is shown in figure 4. the expected behavior is confirmed, the input power tracks the PV output, with peak power provided during midday.

The absence of intermediate storage or DC-DC conversion systems indicates the efficiency of power transfer systems to be the system has minimal conversion losses. Trends related to hydrogen production is illustrated in Figure 5. During peak irradiance hours, the hydrogen flow rate surges and approaches zero in the early morning and late evening. The hydrogen production proportionality to power input validates the electrolysis model. Global energy conversion efficiency from PV to hydrogen is presented in Figure 6. The global energy conversion efficiency PV to hydrogen reached an average efficiency of the system operating between 16% and 18% throughout the day. Minor fluctuations due to non-linear electrolyzer behavior at partial load and temperature also influence overall efficiency. Figure 7 presents a comparative analysis of hydrogen production in sunny and cloudy conditions. The considerable drop in hydrogen output during cloudy scenarios indicates the system's sensitivity to solar irradiance and the need for area-optimized system adjustments. The remaining Figure 8 presents the hydrogen production levelized cost based on solar capital and operational expenditures in regions with high solar insolation. The main point is this: solar hydrogen tech costs less in sunny spots. To sum up, data from the tests back it up. The PV set-ups linked with electrolyzers can give out clean hydrogen. The analysis provides insights that can be used to design and optimize off-grid hydrogen generating systems to be more efficient based on the specific environmental scenarios.

Conclusion

This study presented a detailed analysis of a hybrid photovoltaic-wind system for green hydrogen production in Southern Algeria. The simulation results demonstrate that integrating solar and wind resources can significantly enhance energy availability and system efficiency. The proposed system provides a sustainable and environmentally friendly solution for hydrogen generation, addressing both energy and climate challenges in the region. Key findings include:

- ✓ Hybridization improves overall system reliability compared to standalone PV or wind systems.
- ✓ Maximum power point tracking (MPPT) strategies optimize energy conversion under variable environmental conditions.
- ✓ Green hydrogen production is feasible and can contribute to reducing fossil fuel dependency.

Future work should focus on techno-economic analysis, large-scale deployment strategies, and integration with energy storage systems to ensure continuous operation. The findings support the development of sustainable energy policies and encourage further research on renewable hydrogen production in arid and semi-arid regions.

Recommendations

- ✓ Implement integrated hybrid renewable energy systems in Southern Algeria to optimize green hydrogen production.
- ✓ Conduct long-term performance monitoring to assess system reliability under varying climatic conditions.
- ✓ Investigate economic feasibility and scalability for commercial deployment.
- ✓ Explore advanced MPPT and control strategies to enhance system efficiency.
- ✓ Promote collaboration between universities, research centers, and industry for sustainable energy solutions.
- ✓ Evaluate environmental impacts to ensure compliance with local regulations.
- ✓ Investigate the potential integration of energy storage systems to balance supply and demand.
- ✓ Develop public awareness programs about renewable hydrogen benefits.
- ✓ Support policy development for green energy incentives.

Scientific Ethics Declaration

* The authors declare that the scientific, ethical, and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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Author(s) Information

Zeyneb Charki

Electrical engineering Department, University of Bechar - Tahri Mohamed, Bechar 08000, Algeria

*Contact e-mail: cherki.zeynab@univ-bechar.dz

ORCID iD: <https://orcid.org/0009-0009-0769-8716>

Samira Bediar

Electrical engineering Department, University of Bechar - Tahri Mohamed, Bechar 08000, Algeria.

ORCID iD: <https://orcid.org/0009-0004-0927-4347>

Hachemi Glaoui

Electrical engineering Department, University of Bechar - Tahri Mohamed, Bechar 08000, Algeria.

ORCID iD: <https://orcid.org/0009-0005-0334-8576>

Rachid Dehini

Laboratory of Information Processing and Telecommunications (LTIT), Faculty of Technology, University of Bechar - Tahri Mohamed, Bechar 08000, Algeria

ORCID iD: <https://orcid.org/0000-0002-8769-218X>

*Corresponding author(s) contact email

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Analyzing Energy Quality in the Integration of Renewable Sources into Algeria's Remote Southwest Network

Dehini Rachid

University of Bechar - Tahri Mohamed

Benchikh Lehocine Iftikhar

University of Bechar - Tahri Mohamed

Glaoui Hachemi

University of Bechar - Tahri Mohamed

Bediar Samira

University of Bechar - Tahri Mohamed

Abstract: Independent electricity grids with multiple renewable energy sources face several challenges in ensuring the quality of electricity. This type of network offers the benefits of reliability, efficiency and sustainability. However, the management of such networks requires producers or distributors to deal with issues such as the consequences of the pollution of harmonic currents, the change of renewable energy sources, the challenges of connectivity, and cybersecurity risks. This work examines the consequences of the flow of harmonic currents in an independent, multi-source grid of energy in the far south-west of Algeria (Tindouf area). This research also focuses on understanding the effect of short circuit energy on this type of currents generated by non-linear loads. Through the simulation of this study and analysis, it was observed that harmonic currents, resulting from loads or non-linear intermediates such as converters, have effects on network performance and deterioration of the voltage curve. This results in a decrease in the quality of the electrical product. This work suggests using one of the most reliable solutions, the parallel active filter, in order to reduce harmonic currents, which helps improve network currents and voltage. It also enhances the quality of energy directed to consumers. The results of this study confirmed the importance of proactive measures to manage this type of electrical grid to meet the needs of consumers for this energy, while maintaining its quality and reliability.

Keywords: Renewable energy, Energy quality, Multi-source, Harmonic pollution, Parallel active filters

Introduction

Multi-source electrical grids are systems that simultaneously integrate multiple energy sources to meet the needs of consumers (Hota & Mohanty, 2016). These networks typically involve several power generation technologies such as wind, chemical (fuel cell), solar and hydropower, as well as energy from fossil fuels (Mu et al., 2020). This type of network helps to increase the level of reliability, efficiency and flexibility in the process of supplying energy from the product to the consumers. One of the main advantages of this network is its superior ability to harness several sources of renewable energy along with traditional fossil sources. It also reduces total reliance on fossil fuel energy and contributes to the reduction of unwanted gas emissions (Chen et al., 2024). The regular distribution of electricity generation through various sources ensures continuity of service, in other words, minimizing the effects of supply and demand fluctuations or interruptions from an individual source. These systems are the cornerstone of their operation,) and help make appropriate choices of energy sources from

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a variety of sources based on factors including abundance, cost and environmental considerations (Navarro et al., 2020). In addition, it has the ability to store and distribute this energy efficiently, which helps the flexibility and stability of the network (Barukcic et al., 2023). In general, multi-source power grids are promising solutions to meet today's increasing demand for electricity, while addressing environmental concerns and enhancing energy security (Potrc et al., 2021).

Although this type of network has many good advantages, it faces some problems (Baqar et al., 2022). One of these important challenges is the complexity of the control systems that manage the various energy sources within the same network. This control system must simultaneously provide: generation, transmission and distribution of electricity from multiple sources and coordinate between them, which can be expensive in terms of implementation and maintenance (Bakare et al., 2023; Mel et al., 2022; Strbac, 2008). Demand side management is also a key component that can significantly affect system operation costs and flexibility (Strbac, 2008).. Unlike traditional sources such as coal or natural gas, among other challenges facing this network, is the diversity of energy sources such as wind and solar energy; their generation is controlled by weather conditions and fluctuations during the day, and these changes can pose challenges to ensuring the stability of the network and the continuity of supply of this energy, especially with the lack of sufficient storage solutions for the latter (Bird et al., 2013; Deguenon et al., 2023; Hana, 2023; Oyekale et al., 2020).

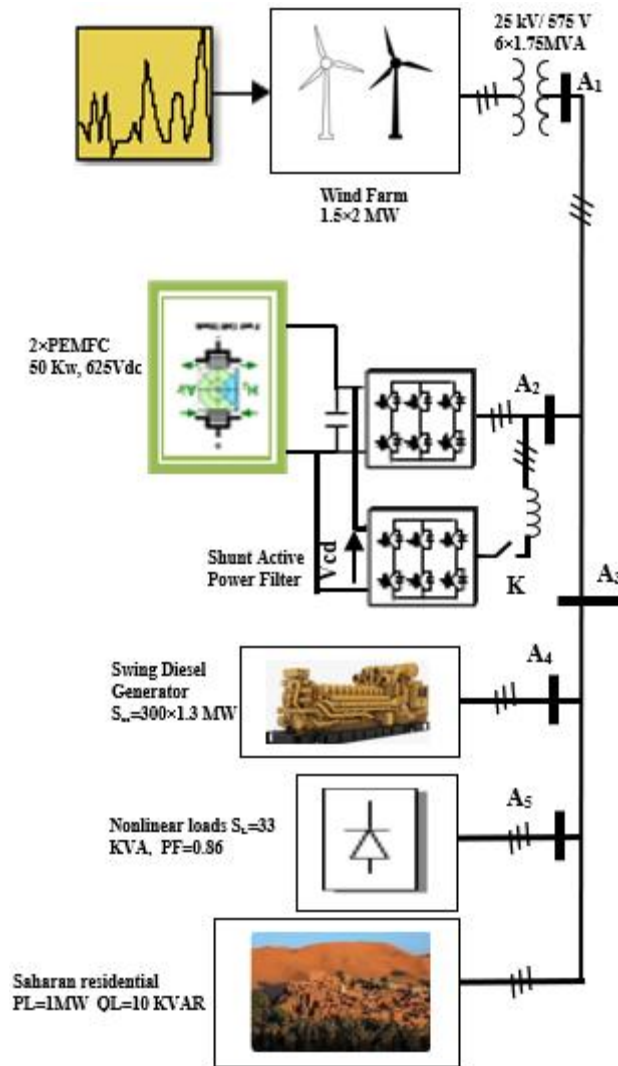


Figure 1. Various energy sources in an independent (Tindouf region in central Algeria).

Multisource electricity grids also, in terms of interconnection, share some challenges; upgrading the existing infrastructure or constructing new transmission lines to weave different energy sources might be snarled in regulatory challenges and opposition from local communities. Additionally, striking a balance between the varied interests (that is, energy producers, consumers as well as policymakers) can complicate the decision-making which in turn slows the shift to multisource grids. Moreover, multisource electricity grids may face

cybersecurity risks owing to the digital control systems and communications networks. These systems are susceptible to cyber-attacks that could result in disruptions of power supplies or even compromise data integrity and confidentiality about stability (Bouramdane, 2023; Krause et al., 2021).

Because of the widespread use of semiconductor based electronic equipment in renewable sources i.e. converters and digital controllers and because of proliferation of non-linear loads in electrical networks, it seems that problem of harmonic current pollution is very clear in these networks. This harmonic current type causes the generation of harmonic voltage when flowing through the network impedance, to be added on the fundamental line-to-line voltage of power system with a non-sinusoidal distorted shape. However, in time, when technology and interests allow these reasons to be removed by using multi-source electrical networks then they will provide an efficient solution for the transition from centralized grids toward a more sustainable and flexible energy future (Eroglu et al., 2021).

In this work, we try to show the pollution due to harmonic currents resulting from the use of various energy sources in an independent network in the Tindouf region (Saharan zone) in west Algeria. In our case, traditional energy, fuel cells and wind energy as shown in figure 1, we also try to compensate these currents and reduce them using the parallel active filter, to obtain the sinusoidal form of the currents and voltages, in order to ensure the quality conditions of the electrical product supplied to consumers (Eroglu et al., 2021; Gbadamosi et al., 2022; Zec & Mikulovic, 2022).

Impact of the Electrical Network's Short-Circuit Power

This study does not focus on the efficiency of smart grid source controls or their configurations. Instead, they delve into how these sources behave within a fault-prone grid, with a particular focus on how short-circuit power in the grid affects harmonic currents generated by nonlinear loads and renewable energy converters. This study aims to highlight the effectiveness of parallel active filters in addressing one of the challenges within networks exposed to the risk of harmonic voltage surge. In addition, we focus our attention on the significant impact that fluctuations in network parameters such as frequency, short-circuit power and load variation have on the proper operation of the network.

To conduct our study objectively and determine appropriate load and network short-circuit power values for analyzing the active filtering of harmonic currents generated by nonlinear loads like static converters, we manipulate the SCC/SN power ratio and observe changes in network parameters. Our findings are visually represented in the following figures:

- SCC refers to the short-circuit power of an electrical network where it connects, known as the Point of Common Coupling (PCC).
- SN stands for the nominal power of the load, which in this case is specified as 1.3 MVA.

Published in previous articles that as the ratio of SCC to SN increases, the active power of the load increases, while the reactive power decreases. According to these studies, it becomes apparent that as the ratio of SCC to SN increases, the active power of the load increases, while the reactive power decreases. This suggests that at a sufficiently high short-circuit power of the electrical network, the diode rectifier bridge consumes practically no reactive power (Hao et al., 2023).

Research depict an improvement in voltage drop with the increase in the SCC/SN ratio. At $SCC/SN = 2000$, there is a greater voltage drop. There's an enhancement in displacement factor with the rise in the SCC/SN ratio. At $SCC/SN = 2000$, the displacement factor can be considered to be equal to one. Once again, the same reference explains how the SCC/SN ratio has a vital influence on THD_v and THD_i. Therefore, the limit does not make any sense in the context of the establishment of harmonic injection limits into the electrical network and design of either passive or active filters. This observation was noted by the IEEE 519-1992, which divided into five different intervals and proposed the restrictions to the harmonic currents permitted to be injected into the electrical supply system by devices that are non-linear. Understanding the importance of the SCC/SN ratio on THD_V and THD_I, a decision was made to study the reliability and efficiency of the passive filter based on a selected case from the intervals specified by the IEEE 519-1992 standard. This case involves harmonic filtering in a weak network where the SCC/SN ratio belongs to the first interval of the IEEE 519-1992 standard ($SCC/SN = 10$).

Study of Installation of a Wind Farm Technical Part

The aim of the study is to develop a wind power project in Tindouf, Algeria, and three possible sites have been suggested focusing on the wind farm onsite including topography, distance to power networks, area available, site accessibility, and restrictions. Site A, on a plateau to the north of the City, is favored by its location in regard to the wind regime, issues of transportation that include proximity to major highways and the power grid and adequate land for the setup of the wind farm as well as good land for the laying of construction bases. An open area, flat ground, and available space for further expansion of the wind farm provides Site B pressed against the rear wall of the diesel producing unit. It carries the prospects of a through-road and connection to the electrical distribution line. The nearby diesel power plant may aid in operation balancing for instance. Site C is further southwest of the power plant than site A, more wind potential may be obtained because site C is at the top of the small hill existing. Its location far away from the main road and the electrical grid makes the development costs of the wind farm higher than other sites, however, as the site contains more space than most of the sites. A met mast has been erected on the front of the Tindouf gate with the purpose of cutting wind speed measurement's reasons, going against the expectation it probably could suffer from some minor disturbance. In the end, it will be the examination of the merits and demerits of a given place in the long run which will be critical in choosing that place.

Table 1. Coordinates of the three sites

Coordinates	North	West	Altitude
Site A	27°44,741'	8°08,660'	445m
Site B	27°37,8768'	8°6,43359'	377,3m
Site C	27°36,8366'	8°6,9744'	401,4m

Pem Fuel Cell and Reference Currents Generation Control

This research focuses on one of the aspects of a system configuration in which Proton Exchange Membrane (PEM) fuel cells and a shunt active power filter are engaged harmoniously. A major emphasis is made on providing utility grid with integrated fuel cell power considering that the fuel cell power is at times fixed. In particular, the setup is able to go beyond injecting chemical energy to the grid, to operate as active power filter parallel type (PAPF) in eliminating reactive current generated from nonlinear load as well as reducing current harmonics.

The purpose is to increase the power of the system and reduce the impact from harmonic currents. In other words, this means that apart from installing a 100KW fuel cell power system, a shunt active power filter is also installed, these three systems are collectively linked to a three-phase grid with nonlinear loads. What is the means of generating the load current harmonic so as to determine its harmonic component? An injected current which is made up has to be produced. This involves taking what is gross current and deducting the reference filter current. In this study, the approach of using the stationary $\alpha\beta$ frame also referred to as the p-q theory is utilized in the evaluation of both active and reactive power. The source voltages and load currents in the $\alpha\beta$ frame are expressed in the following manner:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} = \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (2)$$

In this scenario, e_a , e_b , and e_c stand for the three-phase grid voltages, while i_a , i_b , and i_c represent the load currents. To determine the instantaneous active and reactive powers in the $\alpha\beta$ coordinates, the following formulas are applicable:

$$p_l(t) = e_\alpha(t)i_\alpha(t) + e_\beta(t)i_\beta(t) \quad (3)$$

$$q_l(t) = e_\beta(t)i_\alpha(t) - e_\alpha(t)i_\beta(t) \quad (4)$$

From the aforementioned equation, the instantaneous active and reactive powers may be represented in terms of the dc and ac components, that is:

$$p_l = \overline{p_l} + \tilde{p}_l \quad (5)$$

$$q_l = \overline{q_l} + \tilde{q}_l \quad (6)$$

While $\overline{p}_l$ and $\overline{q}_l$ correspond to AC components due to harmonic currents, $\tilde{p}_l$ and $\tilde{q}_l$ are attributed to DC components stemming from fundamental currents. Estimating the reference currents necessitates $\tilde{q}_l$ computing the instantaneous powers provided by both the source and the Parallel Active Power Filter (PAPF) to the load. If the utility furnishes real and imaginary instantaneous powers p_g and q_g , then the main supply should offer $p_g = \overline{p}_l$, while ensuring $q_g=0$. Concurrently, the PAPF delivers the harmonic component and q_l . Conversely, to offset reactive power and harmonic current, the PAPF provides the real and imaginary instantaneous powers p_f and q_f . Maintaining its sinusoidal waveform, the source current ensures that the PAPF supplies the oscillatory portion of p_l to the nonlinear load.

$$\begin{aligned} p_g &= \overline{p_l} \\ q_g &= 0 \\ p_f &= p_l - p_g = p_l - \overline{p_l} = \tilde{p}_l \\ q_f &= q_l - q_g = q_l \end{aligned} \quad (7)$$

Only the reactive power is provided under these circumstances by the PAPF. As a result, during the steady state, the capacitor voltage level remains constant. Active power balancing between the grid, load, and PAPF must be controlled since the load only absorbs exactly $\overline{p}_l$ of the total power, and if $p_g < \overline{p}_l$, the PAPF delivers the remaining portion to maintain the DC voltage level.

We have: $\overline{p_g} + \overline{p_f} = \overline{p_l}$

As a result, a gain factor k must be added to the previous equations (7) in order to manage the appropriate amount of active power provided by the PAPF [3].

$$k = \frac{\overline{p_g}}{\overline{p_l}} \quad (8)$$

If the gain factor is more than unity, the grid must provide the PAPF with additional active power in order to recharge the capacitor value required at the VDC voltage. The instantaneous reference powers for the PAPF are as follows:

$$\begin{aligned} p_f^* &= \tilde{p}_l + (1 - k)\overline{p_l} \\ q_f^* &= q_l \end{aligned} \quad (9)$$

In the event that the gain factor is less than unity, the capacitor voltage is too high, resulting in a grid power that is less than $\bar{p}_1$ and the remaining portion of $\bar{p}_1$ being delivered by the PAPF to the load. In this instance, the following equation is used to determine the reference currents mandated by the PAPF:

$$\begin{bmatrix} i_{f\alpha} \\ i_{f\beta} \end{bmatrix} = \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix}^{-1} \begin{bmatrix} p_f \\ q_f \end{bmatrix} \quad (10)$$

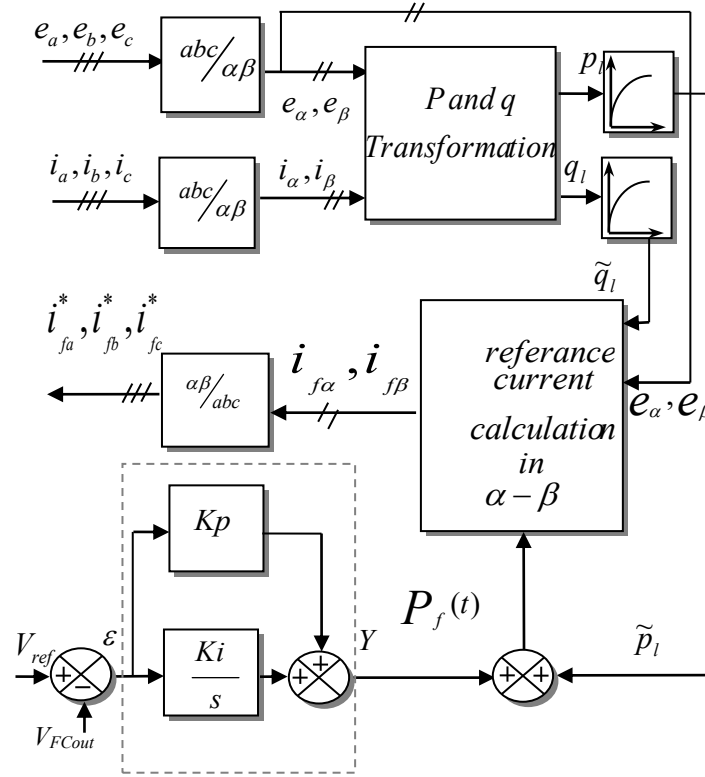


Figure 2. Block diagram for the instantaneous active and reactive power

Results and Discussion

Simulations were undertaken to assess the efficacy of an electrical grid featuring multiple energy sources, operating autonomously from the national grid. Additionally, we aimed to investigate the challenges encountered by this autonomous network under conditions closely resembling real-world scenarios. We introduce a proposed detection and control methodology to the system. The Shunt Active Power Filter (SAPF) is deployed to alleviate harmonics induced by non-linear loads or power supply components like semiconductor-based transformers, especially when the load is in moderate proximity to the grid ($S_{sc}/S_N = 300$), where Nominal power of the load ($S_N = 1.3\text{MVA}$). Detailed parameters of the system model are outlined in Table 2,3.

Table 2. Units for magnetic properties

Parameters	
Supply phase voltage U	220 V
Supply frequency fs	50 Hz
Filter inductor Lf	0.7 mH
Dc link capacitor Cf	0.768474 mF
Vdc	857V
Smoothing inductor Lsmooth	70 μH

Table 3. Parameters of the DFIG

Parameters	
Rated generator power	1.5 MW
Rated voltage	575 V
Rated mechanical speed	12 m/s
Rated frequency	50 Hz
Pole pairs	3
Stator D-axis inductance	0.0136 H
Rotor Q-axis inductance	0.0137 H
Mutual inductance	0.0135 H
Stator resistance	0.012 Ω
Rotor resistance	0.021 Ω
Radius of wind turbine	35.25 m
Number of blades	3
Nominal rotational speed	10 m/s
Optimum power coefficient constant	8.1
Maximum Cp	0.42
Density of air	1.225 kg m ⁻³
Dry friction torque	953 N m
Total inertia of the mechanical	50 kg m ²
Radius of wind turbine	35.25 m

Initially, we'll assess the system's performance without the filter. This involves examining the quality of voltage, current, and power transfer among the system's components.

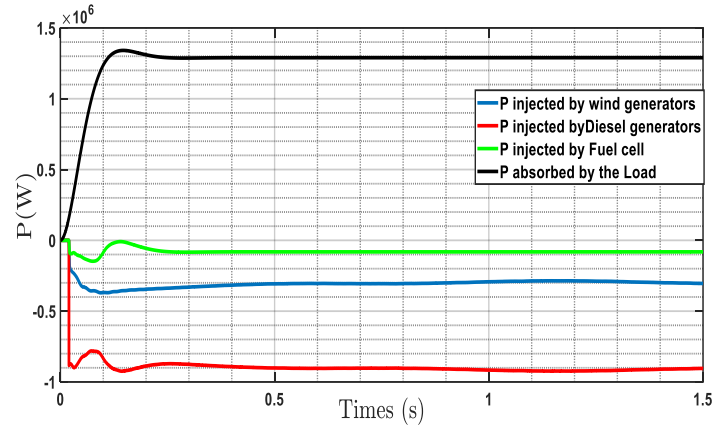


Figure 3. The dynamic exchange of actives powers among the components within the system.

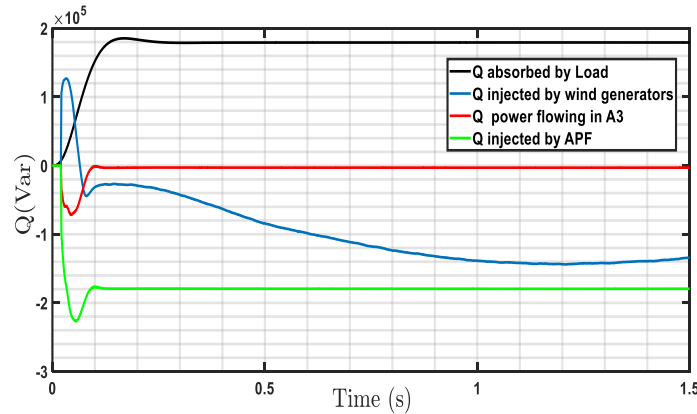


Figure 4. The dynamic exchange of reactive powers among the components within the system.

As seen in Figure 3, many energy sources help in meeting the load demand with respect to the current design so as to bring down the use of polluting gases. Wind energy constitutes 24% of the load energy while that of fuel cell energy comes in at 6%. Loosely speaking, fossil energy has been the major contributor to the energy load range of about 70 percent including losses. This system has helped abate about 30 percent of these harmful

emissions. Power flow of reactive nature greatly affects the choice of equipment... and the stability of the grid. Moreover, it has an impact on the finances. This flow enhances the apparent currents which result in:

- Overreaching and excessive heating of the transformers and cables, and thus active power loss.
- Voltage sags, which increase the reactive power flow and stress the use of electrical equipment on the whole power system. Therefore, it is necessary to reduce its flow through the network, owing to [name] an active filter, which compensates this energy.

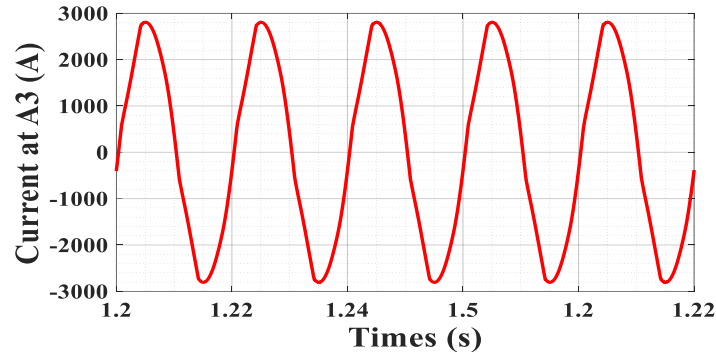


Figure 5. Current at level A3 without A. P. F.

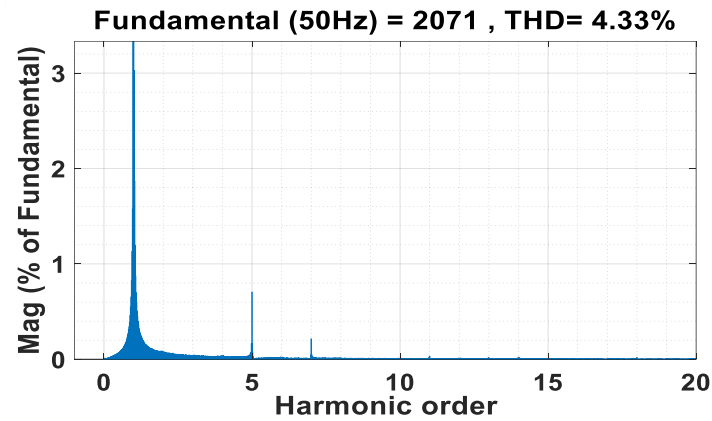


Figure 6. Current at level A3 spectral breakdown without A. P. F.

However, the far more worrying trend is revealed in figures 5 and 6: The electrical current at network level is decreasing; and their distortion factor (harmonic currents) having increased up to a rate of 4.33%! This is above the tolerable limit of international standard IEEE 519-1992. In addition, these harmonic currents flowing in the network impedance cause an attenuation of the magnitude of harmonic voltages. This results in a non-sinusoidal 6.15% voltage with reference to the nominal voltage of the network (Figures 7 and 8). Therefore, the quality of energy is discounted due to this and disturbing the way we are supposed to exist in balance between energy consumer and producer.

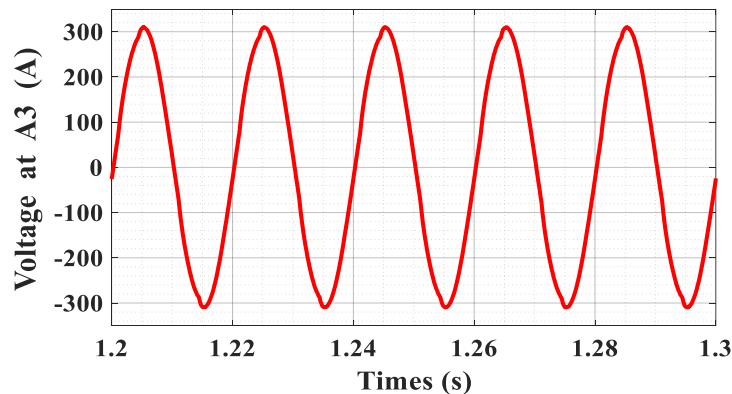


Figure 7. Voltage at level A3 without A. P. F.

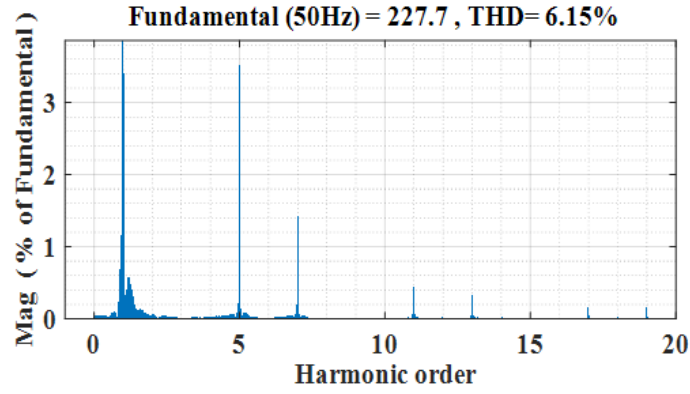


Figure 8. Voltage at level A3's spectral breakdown without A. P. F.

Then, we go on perform a transformer in parallel with the output of the power cell transformer. This clever ingenious addition introduces harmonic currents that are the exact opposite of those present in the network thereby cancelling them out. Consequently, the network stress is increase and thus power transmission quality improves, losses of power getting reduced.

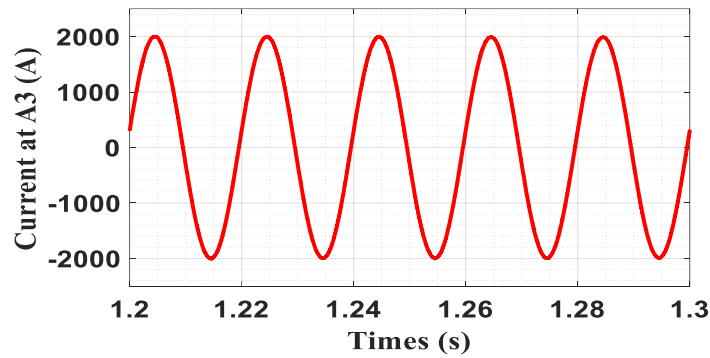


Figure 9. Current at level A3 with A. P. F.

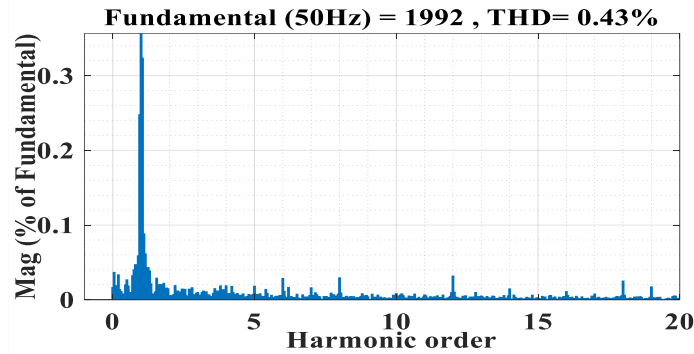


Figure 10. Current at level A3 spectral breakdown with A. P. F.

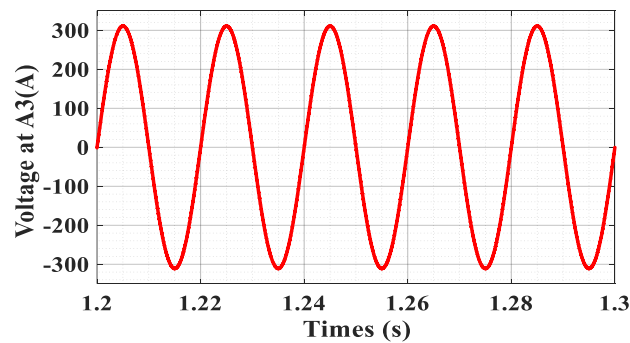


Figure 11. Voltage at level A3 with A. P. F.

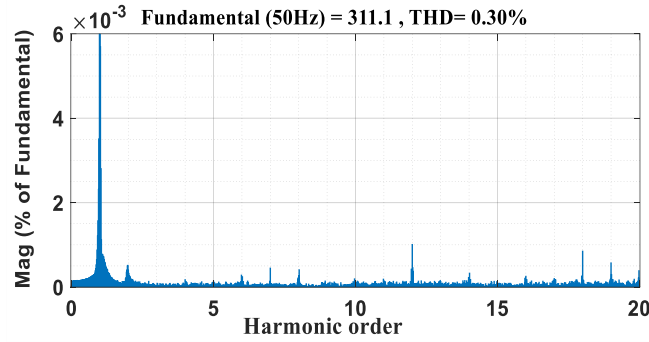


Figure 12. Voltage at level A3's spectral breakdown with A. P. F.

According to the previous figures (see fig 9-10-11-12), after the insertion of the Active Power Filter, in this system with multiple power sources, the network currents improved, becoming THD=0,43%, after removing the harmonic network currents, which represented 4,33% of the fundamental component, with harmonic currents, opposed to them in phase, and injected from the filter. This improvement in performance led to an improvement in network voltages, which decreased from 6,15% to 0,33%, and therefore to a high quality of energy directed to the consumer.

Conclusion

To Sum up, in this article investigate the integration of renewable energy sources to the remote south-west network in Algeria and examine energy quality aspects by showing solutions to improve the quality of electrical product for a consumer. Multi-source electrical networks making use of various energy sources have numerous advantages, primarily linked to their reliability, effectiveness as well as ecological friendliness. But a number of issues need to be resolved — everything from uncontrolled harmonic current pollution through the interconnected grid to dealing with the variability that comes with adding renewables into the generation mix, interconnection problems and cybersecurity risks.

The study aimed to work mainly on the effect of network short circuit power on harmonic current generation by nonlinear loads and renewal power converters. It was determined via simulations and analysis that the harmonic currents were having a big impact on the network's performance, reducing energy product quality.

Consequently, harmonics mitigation was successfully achieved by applying the parallel active filters reducing distortion in network currents and voltages. This improvement in network voltages is main factor to increase the quality of energy transmitted each costumer, resulting from harmonic currents elimination. Results from such a study underscores the imperative of taking preventive method to treat multi-source electrical networks efficiently in order to fulfill energy required levels at elsewhere while keeping up quality and dependability.

Recommendations

In this study, we showed that a multi-source autonomous grid in the Tindouf region can suffer from significant harmonic distortion and voltage issues, especially under weak short-circuit conditions. We therefore recommend that operators of similar remote grids systematically monitor harmonic indices, carefully consider the SCC/SN ratio when connecting new converters, and adopt shunt active power filters to keep current and voltage distortion within acceptable limits. In the longer term, combining wind, fuel cell and conventional units with improved control and storage strategies could further reduce fossil fuel use while maintaining good power quality for local consumers.

Scientific Ethics Declaration

* The authors declare that they are fully responsible for the scientific, ethical, and legal content of this article published in the EPSTEM journal. This work relies on numerical modelling and simulations of power systems and does not involve human or animal subjects, so formal ethics committee approval was not required.

Conflict of Interest

* The authors declare that they have no conflicts of interest related to the research, authorship, or publication of this article.

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Author(s) Information

Dehini Rachid

Laboratory of Information Processing and
Telecommunications (LTIT), Faculty of Technology,
University of Bechar - Tahri Mohamed, Bechar 08000,
Algeria
ORCID iD: <https://orcid.org/0000-0002-8769-218X>
Contact e-mail : dehini.rachid@univ-bechar.dz

Benchikh Lehocine Iftikhar

Laboratory of Information Processing and
Telecommunications (LTIT), Faculty of Technology,
University of Bechar - Tahri Mohamed, Bechar 08000,
Algeria
ORCID iD: <https://orcid.org/0000-0001-9061-0096>

Glaoui Hachemi

Laboratory of Information Processing and
Telecommunications (LTIT), Faculty of Technology,
University of Bechar - Tahri Mohamed, Bechar 08000,
Algeria
ORCID iD: <https://orcid.org/0009-0005-0334-8576>

Bediar Samira

Electrical engineering Department, University of Bechar -
Tahri Mohamed, Bechar 08000, Algeria
ORCID iD: <https://orcid.org/0009-0004-0927-4347>

*Corresponding author(s) contact email

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Research of Pyrrolizidine Alkaloids in *Senecio platyphyllus* Using a UPLC-MS Method

Iamze Kezheradze

Batumi Shota Rustaveli State University

Maia Vanidze

Batumi Shota Rustaveli State University

Ruslan Davitadze

Batumi Shota Rustaveli State University

Aleko Kalandia

Batumi Shota Rustaveli State University

Abstract: The aim of the study was to study the chemical composition of the Georgian endemic plant *Senecio platyphyllus*, in particular, to develop methods for the identification and quantification of pyrrolizidine alkaloids using ultrahigh-performance liquid chromatography-mass spectrometry (UPLC-MS). *Senecio platyphyllus* is rich in pyrrolizidine alkaloids (platyphylline, seneciphylline, sarracine, as well as the N-oxide form of platyphylline) and their content is present in all anatomical parts of the plant. It is known for its spasmolytic activity and is widely used in the therapy of pathologies of the cardiovascular and respiratory systems. The supercritical water extraction (SWE) method was used to prepare the samples, using water containing 2% sulfuric acid, which ensured maximum extraction of alkaloids. The extraction was performed twice, each with a 10-minute cycle, which was optimally selected considering both yield and analysis time efficiency. Qualitative and quantitative analysis of pyrrolizidine alkaloids was performed using a UPLC-MS system (Waters UPLC Acquity QDa), which provided simultaneous, highly sensitive and specific determination of sarracine, senecifilline, platyphylline, and platyphylline N-oxide, based on calibration curves of standard compounds.

Keywords: *Senecio platyphyllus*, Pyrrolizidine alkaloids, Platyphylline, UPLC-MS

Introduction

Senecio platyphyllus (Harishubla) is an endemic plant of Georgia and Turkey, notable for its high content of pyrrolizidine alkaloids, particularly platyphylline, seneciphylline and sarracine. Traditionally, a preparation obtained from it (platyphylline hydrotartrate) has been used to treat abdominal smooth muscle spasms and to dilate the pupil. However, classical extraction technologies employ reagents that are harmful to the environment. Current research focuses on “green” extraction methods (e.g., high-pressure water extraction) and process control by UPLC, which ensure environmental friendliness and high product quality. For the determination of pyrrolizidine alkaloids, ultra-high-performance liquid chromatography combined with mass spectrometric detection (UPLC-MS, Waters UPLC Acquity QDa) was used; this method enabled the simultaneous identification of the alkaloids sarracine, seneciphylline, platyphylline and its N-oxide (Aşçı et al., 2018; Usta et al., 2009; Yayli, 2008). The genus *Senecio* (Asteraceae) is one of the most speciose taxa and is characterized by broad chemical diversity and biological activity. Pyrrolizidine alkaloids (PAs) are particularly important in species of this genus; they are regarded as the principal toxic components and are responsible for hepatotoxicity (Lu et al., 2021). These compounds are widely distributed in the plant kingdom (approximately 3–5%), but their

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occurrence in *Senecio* species attracts special attention from both toxicological and chemotaxonomic perspectives. (Lu et al., 2021; Sadgrove, 2022). Modern studies actively employ high-performance analytical methods, especially liquid chromatography coupled with mass spectrometry (LC-MS, UPLC-MS), for rapid and sensitive identification of pyrrolizidine alkaloids. It has been established that these compounds can be identified by their characteristic fragmentation patterns, such as ions at m/z 120, 122, 124, 138, 140 and 142, which indicate the presence of various types of saturated/unsaturated, lactone or monoester alkaloids (Lu et al., 2021). This approach considerably accelerates analysis and improves method accuracy, which is important for comprehensive characterization of plant chemical profiles. Differentiation of *Senecio* species is often difficult due to morphological similarity; therefore metabolomic approaches gain particular importance. UPLC-MS-based metabolomics is effectively used to distinguish closely related species, for example *Senecio scandens* and *S. vulgaris*, which is especially relevant given their differing toxicities (XiongLi et al., 2011). Such approaches support both pharmacognostic identification and quality control of plant material. Phytochemical studies show that *Senecio* plants contain a wide range of secondary metabolites, including flavonoids, terpenoids, steroids, tannins, saponins and glycosides, although pyrrolizidine alkaloids remain the main focus. For example, senecionine and seneciphylline have been identified in *Senecio vulgaris*, and their structures were confirmed by HPLC and FTIR methods (Kamil Hamid et al., 2016). These compounds play important roles in plant defense and in toxicity. It is noteworthy that the chemical profile of *Senecio* is not limited to alkaloids. Studies indicate that sesquiterpenes (e.g., eremophilanes, bisabolols), flavonoids and other natural compounds are widespread in this genus and often co-occur with alkaloids (Sadgrove, 2022). In some species the sesquiterpene content even surpasses that of pyrrolizidine alkaloids, reflecting a high level of chemical diversity and research gaps, particularly for African species (Sadgrove, 2022). Advances in extraction technologies for bioactive compounds have made significant contributions to the study of *Senecio* chemical composition. Modern methods such as ultrasonic-assisted extraction (UAE), pressurized liquid extraction (PLE) and microwave hydrodiffusion (MHG) provide high yields of alkaloids, including integerrimine and senecionine (Confortin et al., 2021). These technologies not only increase extraction efficiency but also enable identification of a larger number of compounds. *Senecio* species also exhibit notable biological activities. For instance, extracts of *Senecio tenuifolius* showed strong antibacterial activity against *Staphylococcus aureus*, with active fractions identified by GC-MS (Manubolu et al., 2013). Additionally, essential oils of *S. glaucus* and *S. vernalis* demonstrate antioxidant, antimicrobial and cytotoxic activities, attributable to high contents of monoterpenes and sesquiterpenes (Bagci & Kilic, 2012; Balpinar & Okmen, 2019). Chemotaxonomic studies indicate that essential-oil composition of *Senecio* species may be used for species classification. For example, the main components reported in *S. Vernalis* β -phellandrene, 1,8-cineole and caryophyllene oxide reflect that species' chemical specificity (Bagci & Kilic, 2012). Moreover, phenolic compounds and alkaloids found in different extracts determine antioxidant and antimicrobial activities (Balpinar & Okmen, 2019). In conclusion, species of the genus *Senecio* constitute an important subject of pharmacological and toxicological interest. Pyrrolizidine alkaloids remain the most critical constituents of this genus, although other bioactive compounds also play significant roles. Use of modern analytical methods and extraction technologies allows deeper investigation of their chemical composition and biological activities, which is necessary both for safety assessment and for discovery of new bioactive compounds (Lu et al., 2021; Bagci & Kilic, 2012; Balpinar & Okmen, 2019). Unfortunately, in the context of Georgia, recent studies employing modern methods have not been conducted.

Plant Material and Sample Preparation

Senecio platyphyllus (locally known as Kharishubla) is an endemic plant species of Georgia, distributed in the high-mountain region of Adjara. Plant material was collected at the peak of its vegetative period, during the flowering stage, from July through September. The collection site was the high-mountain area of Adjara in western Georgia, specifically Mount Gomi (Fig. 1), at an altitude of approximately 2031.3 m above sea level, which ensures the ecologically clean origin of the samples.

After collection, the plant material was divided into two parts for processing and storage. One part, intended for chemical analyses, was stored at ($-25\text{ }^{\circ}\text{C}$) in order to preserve the original chemical composition of the plant material and to prevent the degradation of biologically active compounds. The second part was subjected to processing. Using a specially developed methodology, extraction procedures were carried out on this portion. The aim of the extraction was the efficient isolation and concentration of the main biologically active constituents, particularly pyrrolizidine alkaloids (platyphylline, seneciphylline and saracin), from the different parts of the plant (roots, stem, leaves, flowers) for subsequent phytochemical analysis and preparation of pharmaceutical formulations.



Dec Degs 41.830524° 42.164656°
Dec Min Secs 41°49'49.9"N 42°09'52.8"E
Figure. 1 Gomi mountain

Instrumentation and Analytical Methods

The study of pyrrolizidine alkaloids was carried out using UPLC-MS chromatographic methods. An analytical column (Phenyl 3.5 μm , 4.6 $\times$ 150 mm) and a mobile phase system consisting of 0.2% formic acid–acetonitrile water in gradient mode were used. For the determination of pyrrolizidine alkaloids, ultra-high-performance liquid chromatography coupled with mass spectrometric detection (UPLC-MS, Waters UPLC Acquity QDa) was employed. This method enabled the simultaneous identification of the alkaloids saracin, seneciphylline, platyphylline and its N-oxide, as well as their quantitative determination using reference standards.

Results and Discussion

A study was carried out on the qualitative and quantitative composition of pyrrolizidine alkaloids in all anatomical parts (flower, leaf, stem, root) of Kharishubla (*Senecio platyphyllus*). Using ultra-high-performance liquid chromatography (UPLC-MS), the following compounds were identified and quantitatively determined:

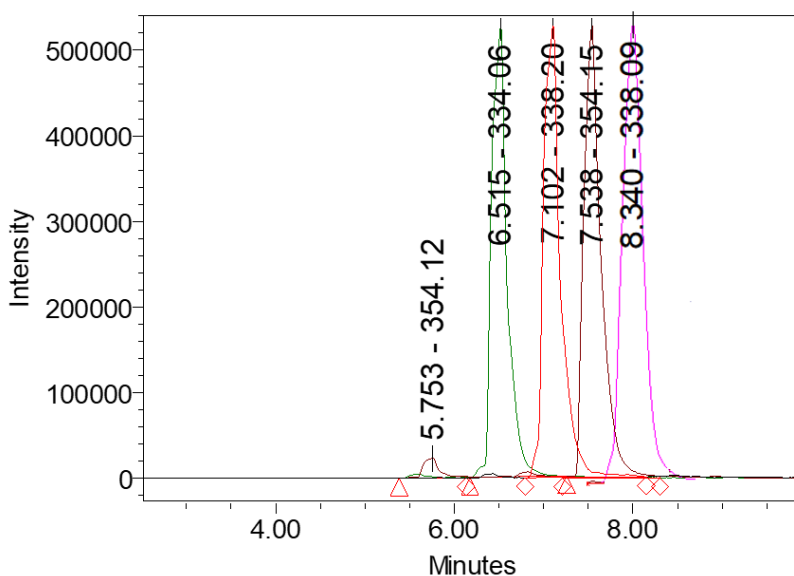


Figure 2. Chromatograms

Substances 1 seneciphylline ESI-MS-m/z 334.06 [M+H], MF: [C₁₈H₂₃NO₅](#) MW: 333.4 g/mol IUPAC Name: (1R,4Z,7R,17R)-4-ethylidene-7-hydroxy-7-methyl-6-methylidene-2,9-dioxo-14-azatricyclo[9.5.1.0^{14,17}]heptadec-11-ene-3,8-dione. (Retention time – 6,515 min)

Substances 2 saracine ESI-MS-m/z 338.20 [M+H], MF: [C₁₈H₂₇NO₅](#) MW: 337.4 g/mol IUPAC Name: [(1S,7R,8R)-7-[(Z)-2-methylbut-2-enoyl]oxy-2,3,5,6,7,8-hexahydro-1H-pyrrolizin-1-yl]methyl (Z)-2-(hydroxymethyl)but-2-enoate. (Retention time – 7,102 min)

Substances 3 platyphylline ESI-MS-m/z 338. 41 [M+H], MF: [C₁₈H₂₇NO₅](#) MW: 337.4 g/mol IUPAC Name: (1R,4Z,6R,7R,11S,17R)-4-ethylidene-7-hydroxy-6,7-dimethyl-2,9-dioxo-14-azatricyclo[9.5.1.0^{14,17}]heptadecane-3,8-dione. (Retention time – 8.340 min)

Substances 4 platyphylline N-oxide ESI-MS-m/z 354.15 [M+H], MF: [C₁₈H₂₇NO₆](#) MW: 353.4 g/mol IUPAC Name: (1R,4Z,6R,7S,11S,17R)-4-ethylidene-7-hydroxy-6,7-dimethyl-14-oxido-2,9-dioxo-14-azoniatricyclo[9.5.1.0^{14,17}]heptadecane-3,8-dione. (Retention time – 7,538 min)

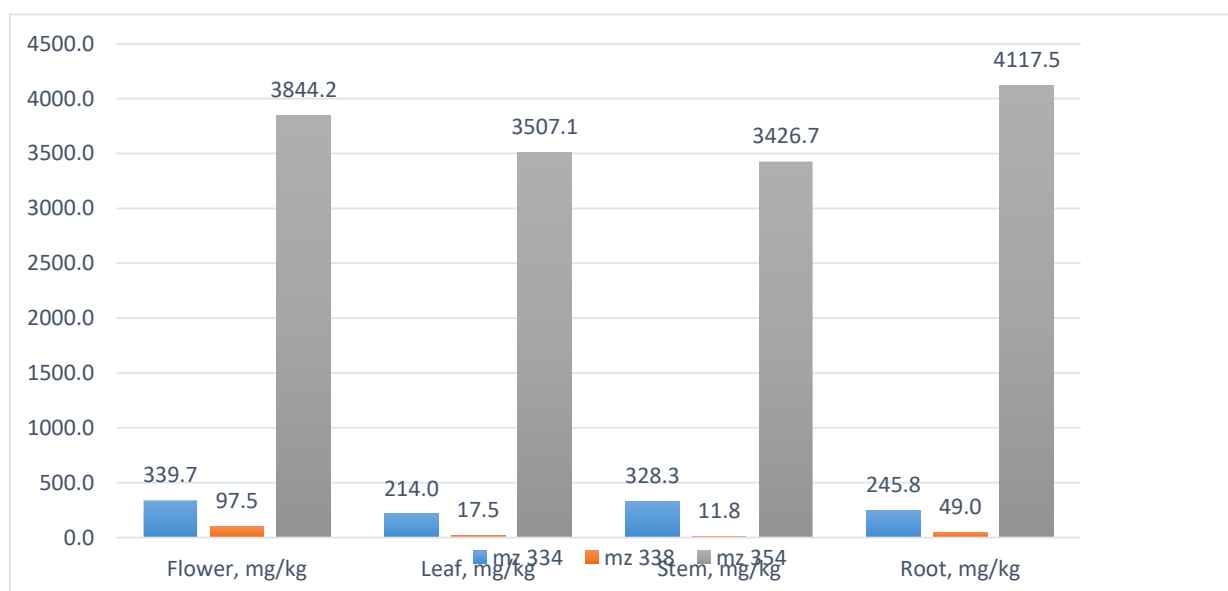


Diagram 1. Quantitative determination of pyrrolizidine alkaloids in Kharishubla (Senecio platyphyllus)

Different levels of pyrrolizidine alkaloids, namely seneciphylline, saracin and platyphylline N-oxide, were detected in various parts of Senecio platyphyllus, indicating the high alkaloid potential of this plant. The N-oxide form of platyphylline is the dominant pyrrolizidine alkaloid and is distributed throughout all parts of the plant, with the highest concentration found in the root (4117.5 mg/kg) and relatively lower levels in the other parts (leaf 3507 mg/kg, stem 3426 mg/kg). The highest content of seneciphylline is observed in the flower (339.7 mg/kg), followed by the leaf (328.3 mg/kg) and the root (245.8 mg/kg), while the stem has the lowest concentration (214.0 mg/kg).

Conclusion

Pyrrolizidine alkaloids of Kharishubla (Senecio platyphyllus) collected from the Gomi Mountain location were studied using supercritical water extraction (SWE) and the UPLC-MS method. The composition of pyrrolizidine alkaloids was compared in all anatomical parts of the plant. Optimal extraction conditions were developed, which increased the yield of the target compounds. Based on the results, it was established that the highest content of platyphylline was recorded in the root, seneciphylline and saracin in the flower.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

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Author(s) Information

Iamze Kezheradze

Batumi Shota Rustaveli State University
Ninoshvili av. 35, Batumi, Georgia
*Contact e-mail: iamzekezheradze@bsu.edu.ge
ORCID iD: <https://orcid.org/0009-0005-7365-4501>

Maia Vanidze

Batumi Shota Rustaveli State University
Ninoshvili av. 35, Batumi, Georgia
ORCID iD: <https://orcid.org/0000-0003-0807-0735>

Ruslan Davitadze

Batumi Shota Rustaveli State University
Ninoshvili av. 35, Batumi, Georgia
ORCID iD: <https://orcid.org/0000-0002-2873-5186>

Aleko Kalandia

Batumi Shota Rustaveli State University
Ninoshvili av. 35, Batumi, Georgia
ORCID iD: <https://orcid.org/0000-0001-9570-9263>

*Corresponding author(s) contact email

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Using Walnut Shell Waste as an Eco-Friendly Aggregate for Concrete

Andrey Chernil'nik

Don State Technical University

Yasin Onuralp Ozkilic

Don State Technical University

Necmettin Erbakan University

Western Caspian University

Abstract: Agricultural production currently generates large quantities of walnut shell waste. Therefore, the issue of efficient disposal of this waste is highly relevant. The aim of this study was to investigate the potential of walnut shells as an environmentally friendly coarse aggregate in concrete production. In the experimental study, concretes were produced with varying walnut shell contents (WS), replacing a portion of the coarse mineral aggregate, ranging from 0% to 50% by volume in 10% increments. Concrete tests were conducted 28 days after production. Density, compressive strength, and water absorption were studied. The composite structure was also assessed using SEM methods, and structural quality factors were calculated. The results showed that concrete density decreased by 15.5% at 50% WS content. It was recorded that with an increase in the volume fraction of WS, compressive strength decreased by 45%, and water absorption increased by 53.4%, respectively. The optimal content WS accounts for 10% by volume. The WS-containing concretes developed in this study are environmentally friendly building materials with a reduced environmental impact and can be effectively used in green construction.

Keywords: Walnut shell (WS), Concrete, Compressive strength

Introduction

Concrete and cement composites are among the most important materials for the construction industry; however, their use is associated with a number of environmental and resource-intensive challenges. In particular, cement production is characterized by significant carbon dioxide (CO₂) emissions, accounting for approximately 8% of global greenhouse gas emissions. Therefore, replacing traditional inert aggregates with alternative materials has become a pressing issue (Murali, 2025; Klyuev et al., 2025). Nutshells, due to their high porosity and water absorption capacity, represent a promising lightweight aggregate. However, their use is associated with a number of issues, including water consumption and physical and mechanical properties. The following paper examines the use of nutshells in cement composites, including various shell types, pre-treatment methods, and optimal dosages for achieving the required characteristics of composite materials (Akulova et al., 2016; Hilal et al., 2021).

The incorporation of nutshells into composite materials such as wood concrete and concrete alters their physical and mechanical properties, but this comes with certain compromises in strength and durability. Specifically, walnut shell-based wood concrete has a density range of 640 to 670 kg/m³, with the optimal density being around 650 kg/m³. Compressive strength after 90 days reaches 3.68–3.90 MPa, but water absorption is 43%, and resistance to subzero temperatures is 35 cycles. When using B30 concrete with the addition of nutshells, density decreases from 2344 to 2148 kg/m³ at a 30% replacement rate. The compressive strength also changes: at 5% substitution it is 45.5 MPa, and at 30% – 34.8 MPa. For the coconut shell-based composite, the compressive strength decreases to 38.0 MPa at 5% substitution and to 26.2 MPa at a replacement level of 30%, while water

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absorption increases from 6.0% to 13.0% (Akulova et al., 2016; Alsalami, 2017; Beskopylny et al., 2023; Nadir & Sujatha, 2018; Stel'makh et al., 2023). In self-compacting concrete, the use of walnut shells leads to a sharp decrease in density from 2162 kg/m³ to 1449 kg/m³ with 40% sand replacement. Compressive strength characteristics also demonstrate a nonlinear relationship: small additions (5%) of walnut shells improve strength properties, but at higher concentrations (30%), the interphase transition zone becomes heterogeneous and defective, which leads to a decrease in overall strength (Puzatova et al., 2024). A similar relationship is observed for concrete using coconut shells, where maximum strength is achieved with 5% replacement, after which a significant decrease in strength is observed with an increase in the proportion of filler (Beskopylny et al., 2023; Hanumanthappa et al., 2026; Stel'makh et al., 2023). In permeable concrete, the fine fraction of walnut shells, replacing part of the sand, helps to increase the efficiency of heavy metal immobilization (Karol et al., 2025).

The addition of walnut shells to ultra-high-performance concrete (UHPC) reduces the autogenous shrinkage of the UHPC matrix and improves hydration (Ren et al., 2025). The use of walnut shells as a replacement for coarse aggregate and steel slag as a replacement for fine aggregate is a rational formulation solution and allows for the production of environmentally friendly concrete with the required performance characteristics (Venkatesan et al., 2021, Boukhelkhal et al., 2023). Walnut shells are an artificially created by-product of recycling and can be used in cement composite technologies as a natural renewable filler, which is also confirmed by numerous other studies (D'Eusano et al., 2023; Khalife et al., 2024; Mhaya et al., 2022; Shafigh et al., 2026). This work is aimed at developing the concept of sustainable development in the construction industry using environmentally friendly building materials.

The possibility of using walnut shell waste as a partial replacement for mineral filler in concrete production will be considered. The scientific novelty of this study lies in the development of new compositions of environmentally friendly lightweight concrete containing walnut shells and the discovery of new relationships between the properties and structure of the composites and the proven formulation parameters. Therefore, the primary objective of the study is to explore the potential of walnut shells as an environmentally friendly coarse aggregate in concrete production and to evaluate the feasibility of using these composites in the construction of various industrial and civil infrastructure facilities.

Materials and Methods

Materials



Figure 1. Walnut shell: (a) walnut shell halves; (b) crushed shell

Before use in concrete, walnut shells were pre-cleaned and subjected to mechanical processing, which was carried out by crushing them in a laboratory jaw crusher to grains with a fraction size of 5-20 mm.

5. Plasticizer PK1 (P) (Polyplast, Moscow, Russia). Properties: density – 1.11 g/cm³.

The following raw materials were used to produce experimental concrete samples:

1. Portland cement CEM I 42.5 H (PC) (CEMROS, Stary Oskol, Russia). Properties: specific surface area – 350 m²/kg; setting time – 3-10 hr-min; setting time – 4-40 hr-min; normal consistency – 30%; compressive strength at the age of 28 days – 54.3 MPa; flexural strength at the age of 28 days – 7.3 MPa;

2. Crushed sandstone produced by (CrS) "Aninsky Mining and Processing Plant" (Anikin village, Russia). Properties: fraction size 5-20 mm; bulk density – 1479 kg/m³; true density – 2661 kg/m³; crushability – 10.1% by weight; content of lamellar (flaky) and needle-shaped grains – 7.5% by weight;
3. Quartz sand (QS) (Subsoil, Samarskoye village, Russia). Properties : bulk density – 1347 kg/m³; the content of dust and clay particles – 0.06%; modulus size – 1.83;
4. Walnut shells (WS) (collected in the Krasnodar region, Russia). Properties: bulk density – 448 kg/m³; Water absorption – 17.6%; content of lamellar (flaky) and needle-shaped grains – 45.6% by weight. The appearance of a walnut shell is shown in Figure 1.

Methods

The production of experimental concrete samples with different WS contents, replacing part of the coarse mineral filler, was carried out in accordance with the recipe presented in Table 1. The coarse mineral filler was replaced by WS by volume from 0% to 50% in 10% increments.

Table 1. Compositions of concrete mixtures with different WS content

Mixture type	PC (kg /m ³)	QS (kg/m ³)	CrS (kg/m ³)	W (L)	WS (kg /m ³)	P (kg/m ³)
0WS	385	712	1093	210	0	3.85
10WS	385	712	984	210	33	3.85
20WS	385	712	874	210	66	3.85
30WS	385	712	765	210	100	3.85
40WS	385	712	656	210	133	3.85
50WS	385	712	547	210	166	3.85

The experimental concrete samples with WS were prepared as follows. Initially, all raw materials were dosed according to the recipe. The prepared raw materials were then poured into a concrete mixer in the sequence PC and QS and mixed dry. Next, coarse aggregates CrS and WS were added with mixing water and a dissolved plasticizer and mixed until a homogeneous consistency was achieved. The finished concrete mixture was poured into metal cube molds measuring 100 x 100 x 100 mm. The molds containing the concrete mixture were compacted on a vibrating platform for 60 seconds. The finished samples were removed from the molds after 24 hours and cured in a curing chamber for 27 days. At 28 days of age, the control and WS concretes were subjected to laboratory tests for density, compressive strength, and water absorption. All laboratory tests were conducted in accordance with standardized methodologies:

1. Density (ρ , kg /m³). The density of concrete was determined on samples dried to constant mass and calculated using formula 1 with an accuracy of 1 kg /m³:

$$\rho = \frac{m}{V} \cdot 1000 \quad (1)$$

where m is the mass of the sample (g);

V – sample volume (cm³).

The density of a series of samples was determined as the arithmetic mean of the test results of three samples.

2. Compressive strength of concrete (R, MPa). Cube specimens were installed in a testing machine and loaded until failure at a constant rate of (0.6 ± 0.2) MPa /s. Compressive strength was calculated using formula 2 with an accuracy of 0.1 MPa:

$$R = \alpha \frac{F}{A} \quad (2)$$

where F is the breaking load (H);

A – area of the working cross-section of the sample (mm²);

α is a coefficient that takes into account the dimensions of the samples (for samples with a side of 100 mm $\alpha = 0.95$). The compressive strength of a series of samples was calculated as the arithmetic mean of three samples, the two with the highest strength.

3. Water absorption of concrete (W, %). Experimental concrete samples were placed in a container filled with water at a temperature of $(20 \pm 2)^\circ\text{C}$ and saturated until the results of two consecutive weighings differed by no more than 0.1%. Water absorption was calculated using formula 3 with an accuracy of 0.1%:

$$W = \frac{m_B - m_c}{m_c} \cdot 100 \quad (3)$$

where m_B is the mass of the dried sample, g;

m_c – mass of dry sample, g.

The water absorption of a series of samples was calculated as the arithmetic mean of three samples.

Results and Discussion

The results of determining the properties of concrete with different WS contents are presented in Figures 2-4.

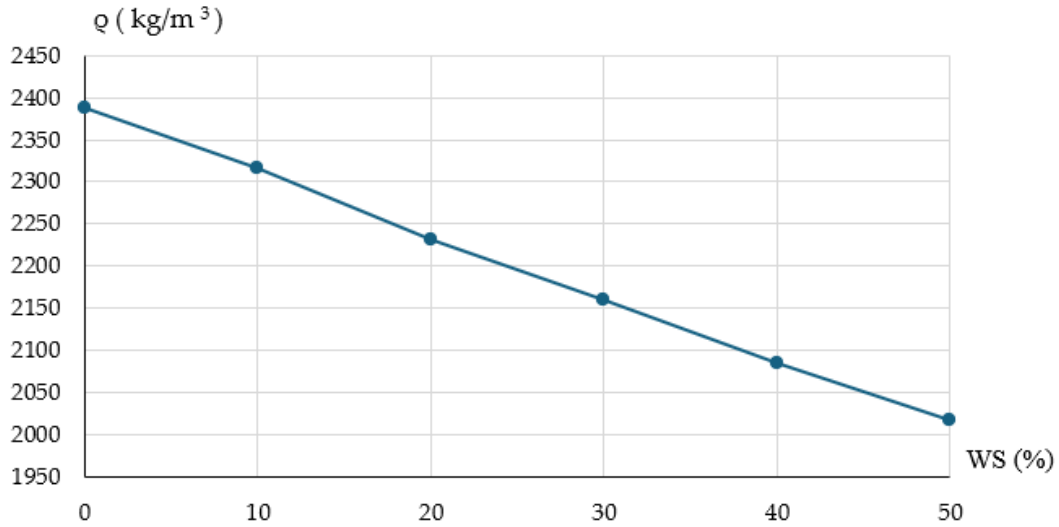


Figure 2. Concrete density versus WS content

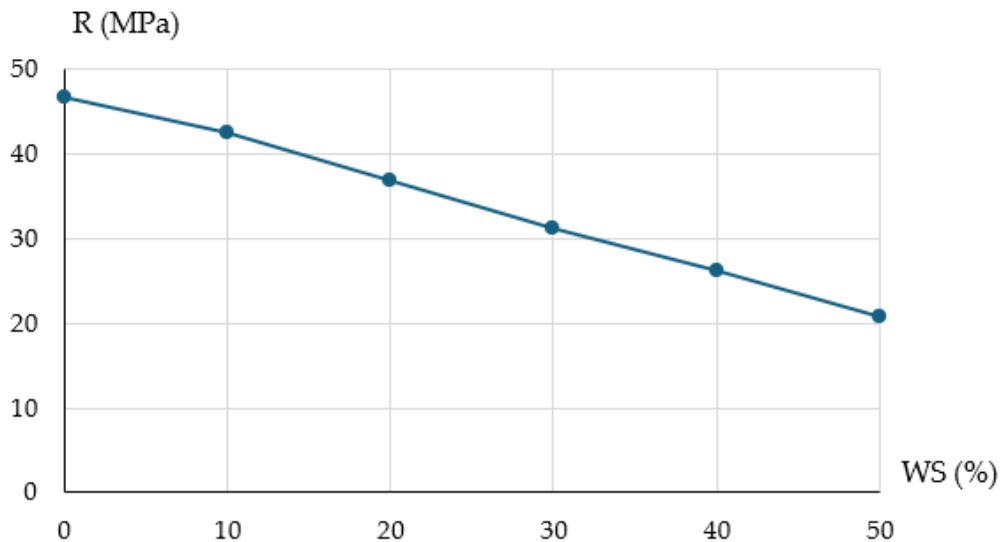


Figure 3. Dependence of compressive strength of concrete on WS content

According to the data presented in Figure 2, concrete density decreases as the WS content increases, replacing part of the coarse mineral aggregate. The control composition has the highest density of 2387 kg /m³. The lowest density of 2016 kg/m³ was recorded for the 50WS composition, which is 15.5% lower than the control composition. The reduction in the density of the composite is achieved by including WS, which has a low density (Edan et al., 2024; Ren et al., 2025).

The dependence of the change in compressive strength of concrete with WS is linear and decreases with increasing content volume fraction of WS. The control composition has the highest compressive strength of 46.7 MPa. Compositions of the 10WS, 20WS, 30WS, 40WS and 50WS types have the following compressive strength values: 42.5 MPa , 36.8 MPa , 32.3 MPa , 28.2 MPa and 25.7 MPa , respectively. For composition 50 WS the reduction in compressive strength was 45%. WS has significantly lower strength compared to CrS and leads to a decrease in the strength properties of the composite (Hanumanthappa et al., 2026; Shafigh et al., 2026).

Water absorption of concrete containing WS tends to increase with increasing WS volume fraction in the concrete. For example, the water absorption of the 50WS composition is 8.9%, 53.4% higher than the control value. Walnut shells are wood-based materials that actively absorb moisture. In the concrete composite structure, WS is saturated with water, increasing water absorption (Cheng et al., 2017).

Based on the results of assessing the density, compressive strength, and water absorption of concrete with varying WS content, it was found that the inclusion of WS reduces its density. However, this decrease in density is accompanied by a decrease in compressive strength and an increase in water absorption. The change in concrete properties (Δ) in % depending on the amount of WS is presented in Table 2.

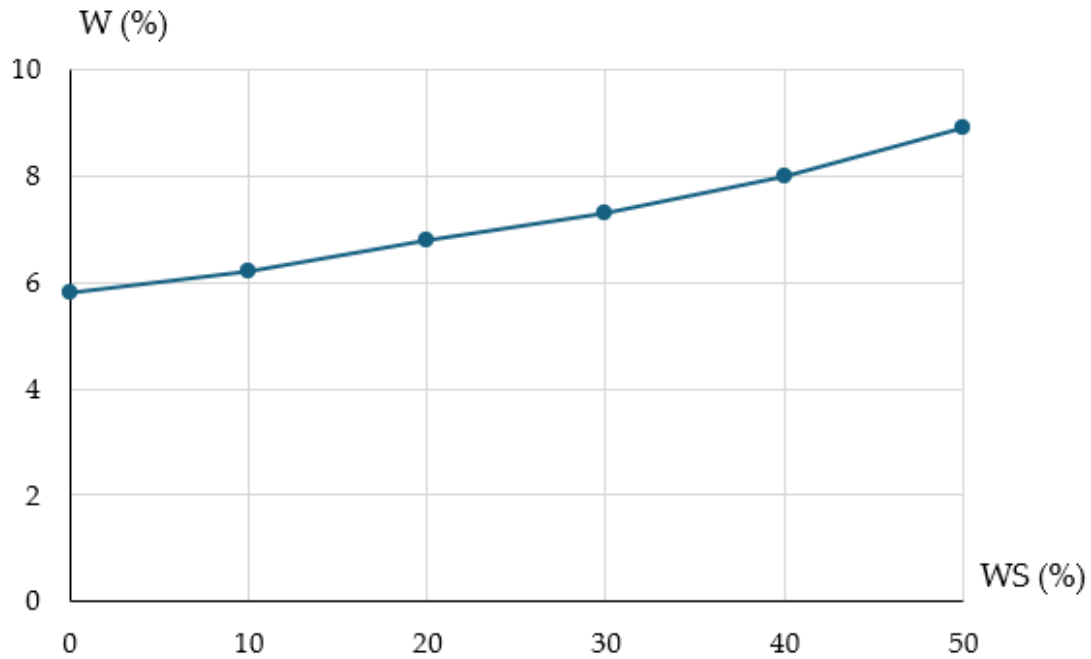


Figure 4. Dependence of concrete water absorption on WS content

Table 2. Concrete characteristics (Δ) in % depending on the amount of WS

Properties	WS content (%)					
	0	10	20	30	40	50
$\Delta \rho$ (%)	0	-3.0	-6.5	-9.6	-12.7	-15.5
ΔR (%)	0	-9.0	-21.2	-30.8	-39.6	-45.0
ΔW (%)	0	+ 6.9	+ 17.2	+ 25.9	+ 37.9	+ 53.4

Further, Figure 5 presents the results of calculating the structural quality factors for concrete with different WS contents. The structural quality factor FC is calculated using formula 4:

$$CCQ = \frac{R}{\rho_{FC}} \quad (4)$$

R – compressive strength (MPa)

ρ – density (g/cm^3).

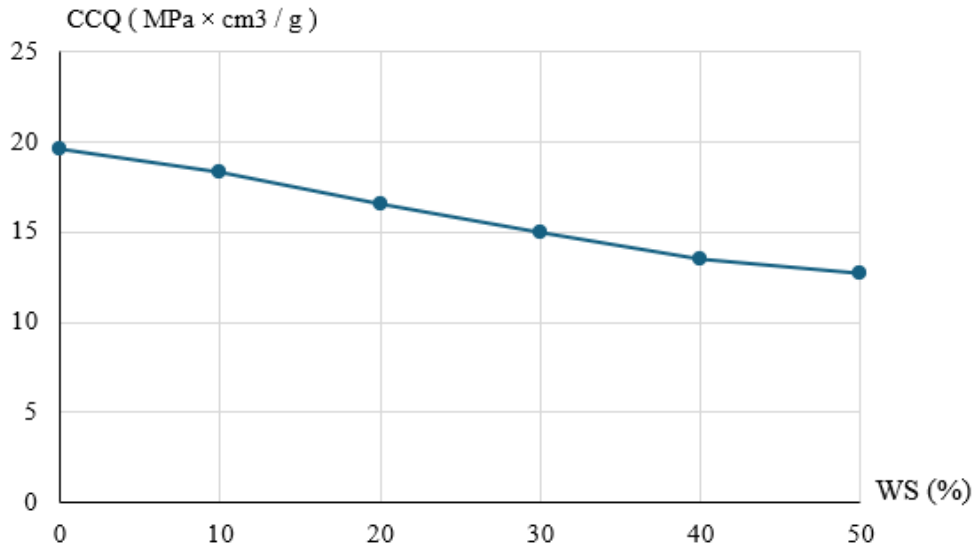


Figure 5. Results of determining the CCQ of concrete with WS

As can be seen from Figure 5, the CCQ values of concrete with 10%, 20%, 30%, 40% and 50% WS content were $19.6 \text{ MPa} \times \text{cm}^3/\text{g}$, $18.4 \text{ MPa} \times \text{cm}^3/\text{g}$, $16.5 \text{ MPa} \times \text{cm}^3/\text{g}$, $14.5 \text{ MPa} \times \text{cm}^3/\text{g}$, $12.6 \text{ MPa} \times \text{cm}^3/\text{g}$ and $10.3 \text{ MPa} \times \text{cm}^3/\text{g}$. A comparative microstructural analysis of the cement matrices of the control concrete and the WS-containing concrete was performed. The results of the SEM analysis are presented in Figure 6.

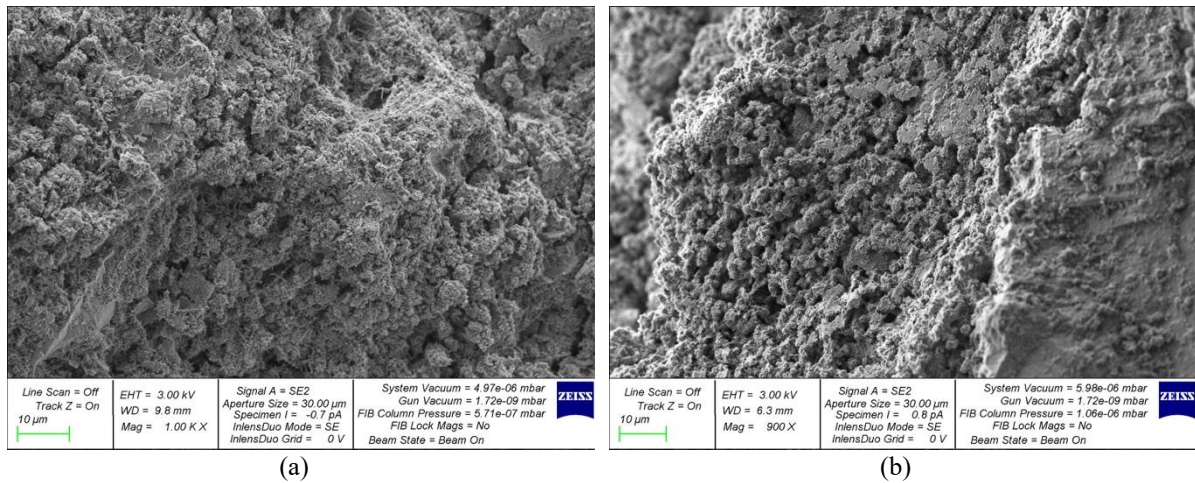


Figure 6. SEM analysis of concrete structure: (a) control concrete composition; (b) concrete composition with WS

The structure of the control composite (Figure 6a) is more organized and ordered compared to the structure of the composite containing WS (Figure 6b). The microstructure image of the control composite shows a more uniform distribution of calcium silicate hydrous (CSH) accumulation zones. The high density of CSH zones directly indicates the higher strength properties of the 0WS type composition (He et al., 2020).

The results obtained during the study are important for the sustainable development of the construction industry. It has been proven that crushed walnut shells can be used as lightweight aggregate in concrete technology. The optimal percentage of walnut shells replacing coarse mineral aggregate without significantly reducing strength properties is 10%. Further, as the volume content increases, With WS, the strength reductions become more significant, and at 50% WS, the compressive strength decreased by 45% compared to the control composition. Perhaps the main limitation of this study is the lack of understanding of durability properties, such as resistance to negative temperature effects and various aggressive chemical influences. This study demonstrates the feasibility

and potential of using walnut shells in concrete products with varying cross-sectional characteristics (variotropic) manufactured using centrifugal molding (centrifugation or vibrocentrifugation). Walnut shell particles, which are lighter than traditional aggregate, will concentrate closer to the inner diameter of the ring-shaped product and influence the final properties of concrete, products, and structures made from it (Shcherban' et al., 2025).

Future research will focus on determining the properties of variotropic concretes and the durability of concretes containing walnut shells, as well as proposing new formulations and technological solutions aimed at increasing the resistance of these composites to aggressive environmental influences (Khalife et al., 2024; Li et al., 2023).

Conclusions

This study developed lightweight, eco-friendly concretes using walnut shells. Experimental composite samples were evaluated for density, compressive strength, and water absorption. Microstructural properties of the composites were analyzed, and structural quality factors were calculated. The density of concrete decreases with increasing volume fraction of WS replacing coarse mineral aggregate. Minimum density 2016 kg/m³ has a composition with 50% WS content. The compressive strength of concrete decreases with increasing volume fraction of WS and ranges from 46.7 MPa for the control composition to 25.7 MPa for the composition with 50% WS content. The inclusion of WS also increases the water absorption of the composites, which ranged from 5.8% for the control composition with 0% WS content to 8.9% for the composition with 50% WS content. Thus, concrete produced with partial replacement of coarse aggregate with WS maintains the basic physical and mechanical properties at the required level and can be effectively used in sustainable green construction.

Recommendations

The results show that the use of walnut shells as a partial substitute for coarse aggregate may be a promising direction for the production of lightweight concrete composites. The most rational is the WS content at a level of about 10% by volume, which ensures an acceptable level of strength while reducing the density of the material. Such compositions can be recommended for use in structures where weight reduction and improved thermal insulation properties are important, for example, in enclosing and curtain elements of buildings. In the future, it is advisable to conduct additional studies on the durability, water absorption and microstructure of concrete with WS, as well as to evaluate its behavior under prolonged operating loads.

Scientific Ethics Declaration

* The authors declare that the scientific, ethical, and legal responsibility for this article published in the EPSTEM journal belongs entirely to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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Author(s) Information

Andrey Chernil'nik

Don State Technical University
Rostov-on-Don, Gagarin Square 1, Russia,
ORCID iD: <https://orcid.org/0000-0002-0103-2587>
*Contact e-mail: achernilnik@donstu.ru

Yasin Onuralp Ozkilic

Don State Technical University
Rostov-on-Don, Gagarin Square 1, Russia.
Necmettin Erbakan University
Konya 42000, Türkiye
Western Caspian University
Baku 1001, Azerbaijan
ORCID iD: <https://orcid.org/0000-0001-9354-4784>

*Corresponding author(s) contact email

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Improving the Energy Efficiency of a Distillery for the Production of Essential Oil

Slav Valchev

University of Food Technology

Abstract: In this study, an energy audit of a distillery for production of essential oils from plant raw materials - rose and lavender was carried out. The equipment of the enterprise envisaged by the project will operate with two types of energy - electricity and thermal energy. Energy consumption analysis is based on electricity and heat consumption of lighting fixtures and technological equipment. The problem areas during the technological process for obtaining essential oils in the enterprise have been examined. The specific energy costs per unit of production and the total energy costs in the enterprise have been determined. Energy saving measures were proposed to reduce the energy costs of electricity and consumed heat energy (natural gas consumption) in distillery. A technical and economic analysis of the energy saving measures was carried out, calculating the total energy savings, economic profitability, payback period, energy savings ratio, energy savings potential and saved carbon emissions into the environment.

Keywords: Energy efficiency, Essential oil, Energy audit

Introduction

The main issues related to optimizing the workflow in essential oil distilleries are related to reducing energy costs in the enterprise and using technologies for processing the resulting waste. For the distillation process of the plant raw material, electrical and thermal energy (energy obtained from burning a certain type of fuel) are used. The reduction of electrical energy is associated with the use of high-efficiency pumps with frequency converters, included in the thermal scheme of the enterprise. In addition to production processes, highly efficient electrical equipment should also be used in the company's auxiliary installations - for example, installing highly efficient lighting fixtures, etc. (Berk, 2009; Ivanov et al., 2021). The reduction of required thermal energy in the enterprise is associated with the provision of cheap fuel and low fuel consumption for obtaining technological steam, necessary for the distillation process (Pipatpaiboon et al., 2025). Low fuel consumption should be ensured by using high-efficiency steam boilers (Chougule et al., 2016; Agustina & Kholifah, 2022; Akterian, 2020; Sichamnan et al., 2022).

The implementation of the described activities will guarantee the receipt of a quality final product (essential oil), an increase in the company's profit, and access of the product to more customers on global markets (Ordinance №E-RD-04-03, 2016; Baev et al., 2026; Kaloyanov et al., 2026; Iliev et al., 2026). This allows them to implement quality standards in their production and to sell their products on the European market (Rasheva, 2011).

Method

The object of the present study for energy efficiency of an industrial system is a distillery - essential oil manufacturer in Bulgaria. The investment intention of the company is to meet the increased production and consumer demand in the European and world markets for various essential products used both in the perfumery industry and for the production of ecological medicines. The geographical location and climatic conditions of

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Bulgaria provide perfect conditions for the growth of oil crops, allowing the production of high-quality and high-yield essential oil products.

The distillation installation is designed to allow the processing of any type of oil product, regardless of its volume, but at the request of the client, the enterprise will mainly process the following essential oil crops:

- Lavender - 336,000 kg/year;
- Rose - 162,000 kg/year.
- In distillery the following technological processes are carried out:
- Distillation apparatus for distillation essential oil;
- Cohobation column for distillation of rose oil;
- Equipment for receiving and supplying process steam;
- Auxiliary equipment.

The choice of energy-saving measures, guaranteeing the highest value energy savings in the form of energy and low carbon emissions released into the environment, requires a detailed energy analysis of the enterprise's energy costs This analysis includes:

- determination of specific energy consumption depending on the production in destillery;
- determining the amount of energy savings as saved energy and as saved carbon emissions to the environment.

The determination of specific electrical energy consumption (SEEC) is carried out using the formula:

$$SEEC = \frac{EEC}{M}$$

where: EEC is electrical energy consumption, kWh/ year and M is manufactured output, kg oil/ year.

The determination of specific thermal energy consumption (STEC) is carried out using the formula:

$$STEC = \frac{TEC}{M}$$

where: TEC is thermal energy consumption, kWh/ year and M is manufactured output, kg oil/ year.

The determination of specific energy consumption (SEC) is carried out using the formula:

$$SEC = \frac{TC}{M}$$

where: TC is total consumption, kWh/ year and M is manufactured output, kg oil/ year.

The net present value (NPV) of energy saving measure is determined by the formula:

$$NPV = \sum_{i=1}^n \frac{B}{(1+r)^i} - I_0$$
$$NPV = B \cdot \frac{1 - (1+r)^{-n}}{r} - I_0$$

where: n – technical/ economic life of the facility, years, r - real interest rate, % and I_0 – investment costs, €.

Coefficient of net present value (NPVQ) is calculated according to the formula:

$$NPVQ = \frac{NPV}{I_0}$$

The pay back period (PB) of energy saving measure is determined by the formula:

$$PB = \frac{I_0}{B}$$

Energy savings ratio (ESR) is calculated by formula:

$$ESR = \frac{TES}{TC} \cdot 100, \%$$

where: TES = B – net annual energy savings, kWh/year, TC - energy consumption of equipment covered by energy saving measures, kWh/year.

Energy savings potential (ESP) is calculated by formula:

$$ESP = \frac{TES}{TC^*} \cdot 100, \%$$

where: TES = B – net annual energy savings, kWh/year, TC* - energy consumption of all equipment installed at the distillery, kWh/year.

The purpose of the study is to propose specific energy-saving measures for the distillery, to assess their economic profitability, to draw up an action plan for their implementation, and to assess the saving effect and the ecological impact of the energy-saving measures on the environment.

Results and Discussion

General Characteristics of the Distillery

The distillery is an existing facility that consists of a production area, a boiler room, an administrative area, and storage facilities for finished products. The distillery employs 6 workers on a permanent basis. The main workforce is seasonal pickers from the city and surrounding villages. The number of workers is determined by the picking company. According to the estimates, the working week will be 5 days, but if necessary, work will be done on weekends, and a rotating shift for pickers will be formed. The working day will continue depending on weather conditions and will last no more than 5 hours. On holidays and pre-holiday days, there will be on-call shifts. This requires the selected workers to have a wider qualification, be well-trained and disciplined. The management of the enterprise is carried out by a manager. An accountant deals with economic and commercial issues.

Water Supply and Sewage

The distillery requires water for drinking, domestic, production and fire-fighting needs. For the use of water for production needs, a borehole with a diameter of 150 mm and a depth of over 36 m is built in close proximity to the main technological consumers, equipped with the necessary facilities, shut-off valves, and automation. The water supply of the site with water for cooling and boiling is carried out with water from the borehole. For this purpose, a pumping station and cooling tower is built. In order to protect against carbonate deposits in the cooling system, the cooling water is subjected to sodium cationic softening. The autonomous groundwater softening installation is installed in the boiler room. The selected cooling tower is an open type with a capacity of 602,000 kcal/h, cooling water flow rate of 5.5 l/s, inlet water temperature 55 °C, outlet water temperature 30 °C. The domestic wastewater is treated in a modular treatment plant. A concrete pit - lagoon with a volume of up to 1500 m³ is formed on the distillery, intended for the temporary storage of waste products /sludge/ during the processing of the rose.

Power Supply to the Distillery

The energy carriers used for enterprise needs are natural gas and electricity. The factory is fully gasified. Natural gas is used to obtain process steam. In connection with the technological needs to ensure the production capacity

of the enterprise, it is necessary to ensure production with high-pressure saturated steam. Two high-pressure steam boilers are planned with a total maximum productivity of 1000 kg/h of steam and 1720 kg/h of steam. The compressed natural gas CNG will be supplied in batteries (modules) of bottles. One module contains: 2 batteries of 53 bottles and 90 l each; total geometric volume for 1 pc. (quantity of natural gas 2098.8 nm³) owned by the supplier of compressed natural gas. The compressed natural gas from the cylinder modules, through a flexible gas connection between the cylinder batteries (on trailers) and the gas regulator station GRP 220/4 bar - 1 unit and a high-pressure hose DN ½" NPT, PN 350, a precision seamless steel pipe for high pressure connected to compression fittings with a cutting ring, will be fed to the gas regulator station (panel) GRP 220/4bar - open installation in a metal cabinet on a concrete platform. The latter is located in the northern corner of the concrete wall, enclosing from the west and part of the north, the concrete platform for the four platforms with modules containing compressed methane. Next to the GRP 220/4 bar, there is also a metal cabinet with dimensions LxWxH 1500x660x1000mm for the installation of 1 wall-mounted gas boiler. The latter isl for preheating the compressed natural gas with pressure 220 bar in a CNG heat exchanger with an external heat source - before pressure reduction.

The project has selected high-efficiency steam boilers, gas burners with modulation of the thermal power, a new generation of water pumps and pink sludge, as well as the necessary automation for their proper management and reduction of their energy costs.

Description of the Production Process

To implement the production program, it is necessary to ensure our own production or supply of the following quantities of raw materials – Table 1.

Table 1. Installed electrical power of the facilities in the enterprise

Product	Distillators	Kg raw material/ cycle	Cycles/ day	Kg raw material/ day	Harvest days per season	Kg raw material/ year	Kg oil/ year
Lavender	2	1200	7	16800	20	336000	3360
Rose	2	550	6	6600	20	132000	40
Rose	1	250	6	1500	20	30000	9

The distillation process takes place under the following parameters:

- Temperature in the range of 25°C – 32°C. Maximum + 35°C;
- Water vapor pressure 0.5 to 0.6 MPa;
- Primary distillation rate – 480 to 510 l/hour, 8 to 10%, - 7.5 s/l;
- Cohobation rate 8.0 to 9.0 s/l
- Distillation duration from 2.0 to 2.5 hours.
- Condensate outlet temperature between 26 °C and 35 °C
- Condenser outlet water temperature around 75°C

The time required to perform the operations in the processing of a rose oil is shown in Table 2.

Table 2. Required time for technological operation – rose oil

Name of the technological operation	Time to perform the technological operation, minutes
Filling the distiller with raw material	20
Releasing steam and distillate flow	10
Distillation	120-150
Emptying and cleaning	15
Total duration, minutes	165-195

A control system has been installed, with the help of which the technological process can be optimally automated and the maximum effect can be realized with minimal energy consumption. For this purpose, the installation has the necessary control mechanisms /motor valves/, controlled by temperature sensors and electronic controllers. The temperatures in the heat exchange equipment is also continuously monitored with electronic thermometers. The ratio of raw material / water in the distiller is 1:4 to 5 parts. The process in the distiller is monitored by an

electronic controller and when the set temperature (+ 30 °C or another experimentally determined) is reached, the valve supplying direct steam to the vessel is fully opened. This time must coincide with the flow of the boiler. The controller maintains the set temperature of the outgoing primary distillate while simultaneously controlling the motor valve of the cold water. With the supply of direct steam, good mixing of the total mass is obtained and the process proceeds at a uniform speed, 8-10%, covering the water losses due to intensive evaporation.

The distillation of lavender is carried out with direct steam at a pressure of 0.5 to 0.6 MPa, and its supply is carried out by gradually opening the steam valve. When an air jet starts to come out of the liquid and distillate begins to flow, the steam is reduced to ensure normal flow of the distillate and to avoid the risk of creating passages in the raw material. The aim is to achieve a 10% speed, which means 7.5 s/l or 480 to 510 l/h of distillation, in order to ensure a normal start of the process. The parameters for processing lavender are as follows:

- distillation rate - during the first 30 min. of the process it is 10%, which means 7.5 s/l , 500 to 510 l/h, after which the rate is reduced to 4-5%, or 200 to 250 l/h.

Control is carried out by the direct steam valve;

- the temperature of the distillate is maintained at 35°C to 40 °C.

It is regulated by the amount of cooled water supplied, by the temperature sensors and the electronic regulator of the motor valve;

- the duration of the distillation is from hour to hour and 20 min.

The time required to perform the operations in the processing of lavender is shown in Table 3.

Table 3. Required time for technological operation – lavender

Name of the technological operation	Time to perform the technological operation, minutes
Filling the distiller with raw material	20
Releasing steam and distillate flow	10
Distillation	60-80
Emptying and cleaning	15
Total duration, minutes	105-125

The distillation process is optimally automated to changes in the technological process, minimizing the subjective factor in its operation and achieving maximum energy savings:

- automatic maintenance of a constant water level in the cold water tanks, through a float system controlling the supply pump of the softening installation, each vessel being equipped with a level indicator tube and an discharge system;
- automatic control of the filling of the distillers with cold/hot water, through a flow meter controlling the hot water pumps to the hot water tank;
- automatic maintenance of the temperature of the primary distillate, through a temperature sensor controlling an electronic regulator and the motor valve of the cooling water of the condenser;
- automatic maintenance of the temperature of the secondary distillate, through a temperature sensor controlling an electronic regulator and the motor valve of the cooling water of the cooler of the cohobation column;
- manual control of the steam shut-off valves;
- automatic stepless regulation of the speed of the water pumps for the primary distillate in order to ensure the most favorable flow rate for the secondary distillation in the cohobation column;
- continuous visual control of the temperature in the heat exchangers by means of electronic thermometers;
- automatic protection of the water pumps by means of a high pressure switch, stopping it when all consumers are turned off;
- automatic protection of the water pumps from low water level by means of a low level switch, mounted on each vessel;
- continuous visual control of the level in the receivers, by means of a level indicator pipe;
- continuous protection of the vessels from overflow, by means of a structurally implemented overflow;
- emptying system connected to the production sewage system of the building;
- manual control of all electrically controlled control devices.

Energy Consumption Analysis

In Table 4 installed electrical power of the facilities in the distillery are shown.

Table 4. Installed electrical power of the facilities in the distillery

Name	Value	Power, kW	Total power, kW	Operating hours, hours/year	Total power, kWh/ year
Technological equipment					
Gas modulating burner, monoblock $Q_t = 110\text{-}1250$ kW; $V = 11\text{-}125$ Nm ³ /h	1	1.81	1.81	960	1738
Gas modulating burner, monoblock; $Q_t = 80\text{-}2000$ kW; $V = 8\text{-}200$ Nm ³ /h	1	3.40	3.40	960	3264
Hot water transfer pump Flow rate 6.8 m ³ /h; Head 16.7 m, 230 V 50 Hz	2	0.75	1.50	600	900
High pressure feed pumps for steam boilers	4	2.50	10.00	600	3000
Submersible drainage pump $Q = 5$ m ³ /h $H=10$ m	1	0.50	0.50	560	280
Open type water cooling tower $V=3$ 6 m ³ /h $Q = 540000$ kkal	1	2.20	2.20	600	1320
Water circulation pump for hot water	2	2.20	4.40	560	2464
Water circulation pump for primary distillate	2	1.50	3.00	560	1680
Water circulation pump - for rose water	1	0.35	0.35	560	392
Submersible drainage pump $V = 5$ m ³ /h $H = 10$ m	1	0.50	0.50	560	280
Pumping-hydro system (1 working + 1 spare pump) $V = 20$ m ³ /h $H = 40$ m, $N = 4$ kW complete. available with electric panel and expansion tank 200 l + automatics-pressure operation	1	2.00	2.00	600	1200
Submersible drainage pump $V = 5$ m ³ /h $H = 10$ m	1	0.50	0.50	560	280
Pumping-hydro system for hot water (1 working + 1 standby pump) $V = 20$ m ³ /h $H = 25$ m, $N = 4$ kW complete with electric panel automatics-new on a drawing tank	1	2.00	2.00	600	1200
Electric hoist for monorail (load capacity 3 tons)	1	3.00	3.00	960	2880
Harnessing unit for 2.00 m ³	1	3.00	3.00	960	2880
Electronic scale - desktop	3	0.10	0.30	960	288
Electronic scale – for monitoring	3	0.10	0.30	960	288
Electric water heater 10 liters	2	3.00	6.00	300	1800
Vertical electric water heater 50 liters	1	3.00	3.00	300	900
Vertical electric water heater 80 liters	3	3.00	9.00	300	2700
Computer	5	0.35	1.75	150	262.5
Printer	5	0.35	1.75	150	262.5
Total usable power			60.26		30259

		Lighting equipment			
LED light 40W, IP21	12	0.04	0.48	960	192
LED light 24W, IP44	36	0.024	0.864	960	69
LED light 2x30W IP65	27	0.06	1.62	960	144
LED light 2x24W IP65	19	0.048	0.912	250	120
LED light 10W	1	0.010	0.010	250	216
LED light 12W, IP 44	3	0.012	0.036	250	405
LED floodlights 100W	4	0.10	0.40	250	228
LED floodlights Ex 2x 36 W	2	0.072	0.144	250	3
LED floodlights Ex 100 W	3	0.10	0.30	250	9
LED 1x8W, for evacuation lighting with pictogram IP65	40	0.008	0.32	250	80
Street light 80W, IP66	36	0.08	2.88	250	720
Total usable power			7.966		2186
Total power			68.226		32445

Based on the data from the previous table, percentage distribution of energy consumed in distillery is presented on Figure 1.

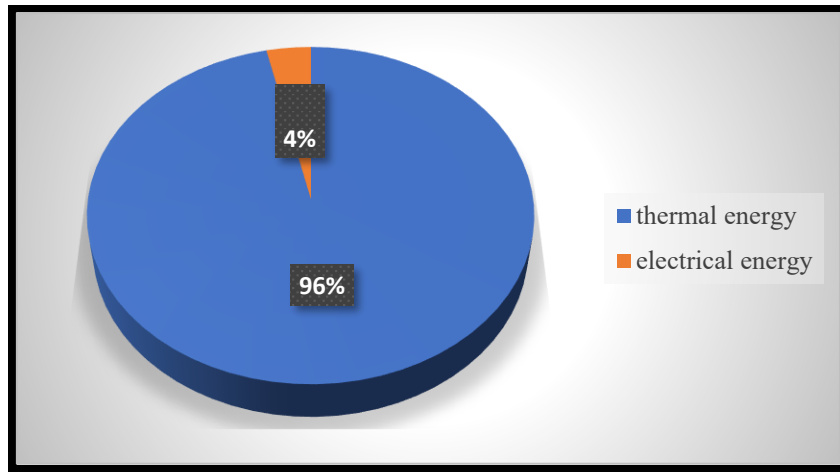


Figure 1. Percentage distribution of energy consumed in distillery

The data shows that thermal energy is used as a priority at the distillery. On Figure 2 a percentage distribution of electrical energy consumed in distillery is shown.

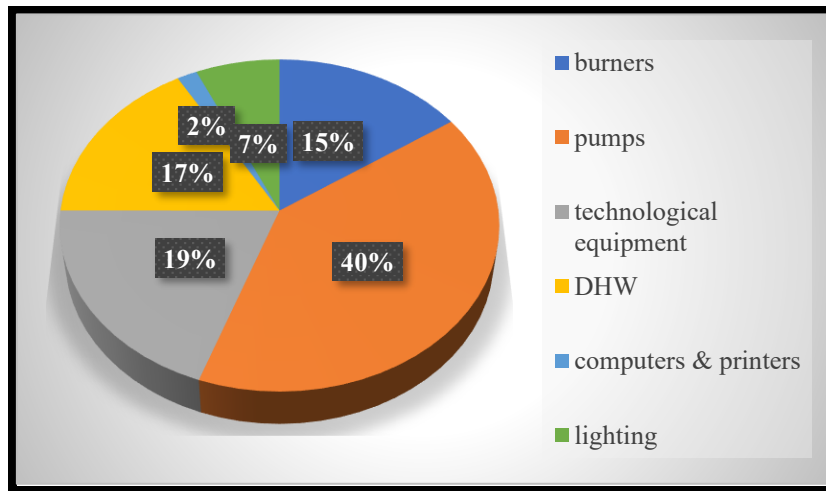


Figure 2. Percentage distribution of electrical energy consumed in distillery

The data shows that 40 % of electrical energy in distillery are consumed by different pumps in distillery. On Figure 3 a percentage distribution of thermal energy consumed in distillery is shown.

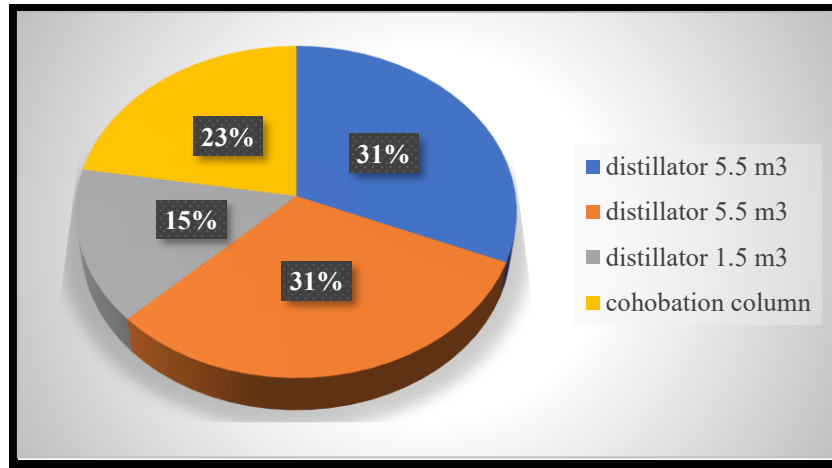


Figure 3. Percentage distribution of thermal energy consumed in distillery

In Table 5 total thermal power for steam boilers are shown.

Table 5. Total thermal power for steam boilers

Name	Value	Steam production, kg/hour	Total power, kW	Operating hours, hours/year	Total power, kWh/ year
Three-pass steam boiler with steam production 1000 kg/hour of steam, working pressure 12 bar.	1	1000	708(+1132)*	300	552000
Three-pass steam boiler with steam production 1720 kg/hour of steam, working pressure 12 bar	1	1720	1132	300	339600
Total usable power					891600

* For lavender processing, both boilers operate simultaneously.

In Table 6 total thermal consumption for distillation apparatus and cohobation column is shown.

Table 6. Consumed electrical energy after energy-saving measures

Name	Value	Steam consumption, kg/hour	Total thermal consumption, kW
Distillation apparatus with a capacity of 5.5 m ³	1	840.00	555
Distillation apparatus with a capacity of 5.5 m ³	1	840.00	555
Distillation apparatus with a capacity of 1.5 m ³	1	400.00	264
Cohobation column with a capacity of 2.5 m ³ /hour	1	600.00	396

Proposed Energy Saving Measures

After analyzing the energy consumption of the site, the following conclusions can be made:

- The site will consume a greater amount of thermal energy than electrical energy;
- Electrical energy is primarily consumed by the pumps in the distillery.

Energy-saving measures are proposed to improve the efficiency of steam boilers, as well as to reduce the electrical energy consumed by the various pumps in the distillery. In this sense, proposals for reducing the energy costs of the enterprise can be made in the following directions:

ESM 1: It is proposed to install economizers – 2 pcs. (flue gas – water heat exchangers), which will utilize the waste heat from the flue gases of the steam boilers. In economizer, the flue gases are cooled to condensation temperature of water vapor contained in them, and the heat released from the cooling of the flue gases and the condensation of the water vapor is transferred through a heat exchange surface to the incoming feed water. This

directly affects the natural gas consumption of the modulating burner of the steam boiler, namely – savings of 11% (98076 kWh/year) of the total thermal energy generated by the two boilers are expected. Part of the hot water obtained in the economizer can be used to heat domestic hot water in 3 volumetric boilers, each with a capacity of 80 liters with a built-in coil. The expected savings of electricity for heating water in the boilers is 90% (2430 kWh/year) of the total electricity consumed by the three boilers.

ESM 2: It is proposed to install frequency inverters on the electric drives of each of the four linear feed pumps for the steam boilers. As a result of the implementation of the measure, a 50% reduction in the electricity consumption of the pumps (1500 kWh/year) is expected.

ESM 3: It is proposed to install frequency inverters on the electric drives of the two linear transfer pumps for hot water. As a result of the implementation of the measure, a 50% reduction in the electricity consumption of the pumps (450 kWh/year) is expected.

ESM 4: It is proposed to install frequency inverters on the electric drives of each of the four pumps of the pump hydrophore systems. As a result of the implementation of the measure, a 50% reduction in the electricity consumption of the pumps (1200 kWh/year) is expected.

ESM 5: It is proposed to install a frequency inverter on the electric drive of the cooling tower fan. As a result of implementing the measure, a 50% reduction in the fan's electricity consumption (660 kWh/year) is expected.

Technical and Economic Analysis of Energy Saving Measures

A comparison of specific energy consumption before and after energy saving measures is shown in Table 7.

	Before ESM				After ESM			
	Energy consumption for related measures activities	Produced output	Specific energy consumption	Corrected energy consumption for related measures activities	Energy consumption for related measures activities	Produced output	Specific energy consumption	
	kWh/year	kg/year	kWh/kg	kWh/year	kWh/year	kg/year	kWh/kg	
ESM 1	894300	3409	262.3	894300	793794	3409	232.9	
ESM 2	3000	3409	0.9	3000	1500	3409	0.4	
ESM 3	900	3409	0.3	900	450	3409	0.1	
ESM 4	2400	3409	0.7	2400	1200	3409	0.4	
ESM 5	1320	3409	0.4	1320	660	3409	0.2	
Total:	901920	3409	264.6	901920	797604	3409	234.0	

The parameters of the energy efficiency measures are calculated based on the following data:

- Carbon dioxide (CO₂) emissions of electricity are 0.819 kgCO₂/kWh, and for natural gas are 0.202 kgCO₂/kWh;
- Price of electricity supply – 0.22 €/kWh;
- Price of compressed natural gas supply in bottles – 0.25 €/kWh;
- Heat of combustion of natural gas fuel - 9.305 kWh/ Nm³;
- Duration of technical/economic life of the facility is n = 20 years;
- Real interest rate, r = 3.00 %.

Calculation whether the measures are cost-effective (values of NPV, NPVQ) and their payback period (PB) are presented in Table 8.

Table 8. Assessment of the economic effectiveness of energy saving measures

	B, kWh/year	B, €/year	I ₀ , €	PB, years	NPV, €	NPVQ, -
ESM 1	100506	25053.60	77572.00	3.1	+296246.87	3.8
ESM 2	1500	330.00	2200.00	6.7	+2709.57	1.2
ESM 3	450	99.00	970.00	9.8	+211.86	0.2
ESM 4	1200	264.00	2200.00	8.3	+502.87	0.2
ESM 5	660	145.20	475.00	3.1	+1727.65	3.6
Total:	104316	25891.80	83417.00	3.2	-	-

The values of energy saving ratio (ESR), energy saving potential (ESP) and ecological equivalent (t CO₂/ year) of energy saving measures are shown in Table 9.

Table 9. ESR, ESP and ecological equivalent of energy saving measures

Energy saving measures	Energy carrier	Energy savings			Ecological equivalent t CO ₂ / year
		TES, kWh/year	ESR, %	ESP, %	
ESM 1	electricity+thermal	100506	11.2	-	21.8
ESM 2	electricity	1500	50.0	-	1.2
ESM 3	electricity	450	50.0	-	0.4
ESM 4	electricity	1200	50.0	-	1.0
ESM 5	electricity	660	50.0	-	0.5
Total:	-	104316	11.6	11.3	24.9

Conclusion

The energy audit of the distillery showed the following results:

- Although the system has the necessary automation to control the technological process, it can be optimized by increasing the efficiency of steam boilers and by installing controllers for frequency control of the pump motors in the distillery;
- The net present value of each of the measures is a positive value, this means that all energy-saving measures are economically profitable;
- The sequence for implementing the measures according to the values of the net present value coefficients should be: first implemented measure is ESM 1 (3.8), followed by ESM 5 (3.6), ESM 2 (1.2), ESM 3 (0.2) and ESM 4 (0.2);
- The payback periods of the measures vary from 3.1 to 9.8 years, and for the entire package of energy-saving measures the payback period is 3.2 years.
- After implementing the described measures, annual savings of:
*98076 kWh of thermal energy are expected, which is equivalent to savings in the consumed natural gas in the amount of 10540 Nm³. The total annual savings from the reduced consumption of natural gas are in the amount of 24519.00 €.
- * 6240 kWh of electricity. The total annual savings from the reduced consumption of electricity are in the amount of 1372.80 €;
- The total annual costs for the distillery are reduced by 25891.80 €.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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Author(s) Information

Slav Valchev

University of Food Technology

26 Maritza Boulevard, Plovdiv, Bulgaria,

ORCID iD: <https://orcid.org/0009-0006-6303-0188>

Contact e-mail: slavvalchev@uft-plovdiv.bg

*Corresponding author(s) contact email

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Study of Phenolic Compounds of *Rhododendron ponticum* Distributed in Adjara

Salome Gogitidze

Batumi Shota Rustaveli State University

Maia Vanidze

Batumi Shota Rustaveli State University

Jeiran Putkaradze

Batumi Shota Rustaveli State University

Maia Kharadze

Batumi Shota Rustaveli State University

Aleko Kalandia

Batumi Shota Rustaveli State University

Abstract: *Rhododendron ponticum* L. represents an important relict species within the flora of Georgia, including the Adjara region, and is characterized by significant ecological value and a rich composition of biologically active metabolites. According to the available scientific literature, this species is particularly rich in polyphenolic compounds, especially flavanol-type catechins, which are widely recognized for their pronounced antioxidant, antimicrobial, and cytoprotective properties. Nevertheless, the phenolic composition and quantitative distribution of phenolic metabolites in *R. ponticum* populations growing in Georgia remain insufficiently investigated. The present study aimed to identify and characterize the phenolic compounds present in the leaves of *R. ponticum* distributed in Georgia using qualitative and quantitative analytical approaches. The conducted analysis revealed the presence of several major phenolic constituents. Gallocatechin was detected, demonstrating the strong antioxidant potential of the species. In addition, catechin dimers, namely proanthocyanidins (Procyanidin B1, B2, and B3), were identified, which are known to contribute significantly to free radical scavenging mechanisms. Furthermore, several other phenolic metabolites were identified, including gallic acid, quercetin-3-O-glucoside (isoquercitrin), quercetin-3-O-rutinoside (rutin), kaempferol-3-O-glucoside, and kaempferol-3-O-rutinoside. The obtained findings confirm that *R. ponticum* growing in Georgia represents a valuable natural source of phenolic compounds and demonstrates considerable potential for further pharmacological and biochemical investigations.

Keywords: *Rhododendron ponticum*; Polyphenols; Proanthocyanidins; Antioxidant activity.

Introduction

Rhododendron ponticum L. belongs to the family (Ericaceae) and is a widely distributed evergreen plant known for both its ornamental and medicinal importance. The genus *Rhododendron* includes more than 1,200 species and is characterized by a rich phytochemical composition, which determines its diverse biological activity (Kumar, V., 2018). In traditional medicine, the leaves of *R. ponticum* are used to treat inflammatory processes, rheumatic pain, and toothache, indicating its potential pharmacological effects (Erdemoglu, 2019).

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In this species, multiple groups of bioactive compounds have been identified, including phenolic acids, flavonoids, tannins, and diterpenes, which are responsible for its antioxidant, antimicrobial, and anti-inflammatory properties (Gürbüz et al., 2021; Kula et al., 2022). Phenolic compounds are particularly important, as they play a significant role in reducing oxidative stress and are actively used in the production of functional foods and pharmaceutical preparations (Shahidi & Yeo, 2018).

The isolation of bioactive components and the evaluation of their biological activity yield significant results. Phytochemical studies show that *R. ponticum* contains numerous bioactive compounds, especially phenolic compounds and flavonoids. Based on HPLC-DAD analysis, at least 15 phenolic components have been identified, among which catechin and epicatechin are predominant (Sıcak, Y., 2024). These compounds are known for their strong antioxidant properties and play an important role in neutralizing free radicals. In addition, phenolic acids (gallic, ferulic, caffeic), flavonoids (quercetin, apigenin), and terpenoids have been identified in other *Rhododendron* species, indicating a general biochemical similarity within the genus (Shootha, D., 2022). *Rhododendron ponticum* is distinguished by a high content of flavonoids and phenolic compounds, which constitute the main group of bioactive components in this plant. Studies have confirmed the presence of compounds such as quercetin, kaempferol, catechins and chlorogenic acid, which are characterized by strong antioxidant activity and are found in the leaves and flowers of the plant (Demir et al., 2019; Popescu et al., 2020). In addition to simple phenolic compounds, *R. ponticum* contains complex flavonoid compounds that contribute to its anti-inflammatory and antimicrobial activity (Gürbüz et al., 2021; Kula et al., 2022). A high concentration of phenolic compounds is also associated with the plant's adaptive ability under environmental stress conditions, particularly in regions with high humidity such as Western Georgia (Kandelaki, M., 2021).

Catechins in *Rhododendron ponticum* represent an important group of flavonoid compounds found mainly in the leaves and flowers. They are characterized by strong antioxidant activity and play a significant role in neutralizing free radicals and protecting the plant from oxidative stress. Catechins are also associated with antimicrobial and anti-inflammatory effects, which determine the biological activity of this species (Demir et al., 2019; Gürbüz et al., 2021). Various forms of catechins have been identified in the leaves of *Rhododendron ponticum*, including epicatechin.

Phenolic carboxylic acids represent one of the important groups of bioactive components in *Rhododendron ponticum*. Various studies have shown that chlorogenic acid, caffeic acid, and gallic acid are present in the leaves and flowers of the plant, all of which are distinguished by strong antioxidant activity (Demir et al., 2019; Popescu et al., 2020).

These compounds effectively neutralize free radicals and protect cells from oxidative damage, playing an important role in the prevention of chronic diseases (Shahidi & Yeo, 2018). Over the past decade, research has increasingly focused on the detailed analysis of the phenolic profile of *Rhododendron ponticum*, highlighting its potential as an alternative source of natural antioxidants (Demir et al., 2019). At the same time, special attention is paid to the variability of its chemical composition under the influence of ecological factors such as climate, soil type, and altitude above sea level, which determine the quantitative and qualitative characteristics of bioactive substances (Popescu et al., 2020).

Despite existing studies, the phenolic composition of *Rhododendron ponticum* and its variability under the ecological conditions of the Adjara region have not yet been sufficiently studied. This issue is particularly relevant, as Adjara is characterized by diverse climatic and geographical conditions, which may significantly affect the profile of bioactive compounds in the plant. Therefore, the present topic is important both from a fundamental scientific perspective and from a practical point of view, in terms of identifying new local sources of natural antioxidants and their rational use.

Plant Material and Sample Preparation

The object of the study was rhododendron leaves (*Rhododendron ponticum* L.). The samples were collected in Western Georgia, specifically in the Adjara region, from three different locations: Keda Municipality, village Tskhmorisi (41°38'20" N, 42°02'47" E), at an altitude of 532 m above sea level; Keda Municipality, village Kharaula (41°36'00" N, 41°58'00" E), at an altitude of 880 m above sea level; and Machakhela Valley (41°31'32" N, 41°44'51" E), at an altitude of 350 m above sea level.

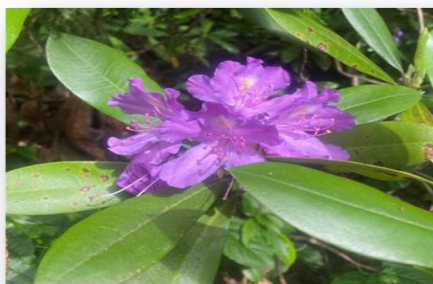


Figure 1. *Rhododendron ponticum* L.

For the extraction of rhododendron samples, 50 g of sample was taken; 20% ethanol was used as the extractant. The sample was homogenized (1–2 min) using a homogenizer, then placed in an ultrasonic bath for 30 minutes, and finally filtered under vacuum conditions. This process was repeated until the solvent became colorless (complete extraction).

Research Methods

Quantitative determination of total phenols - by the Folin–Ciocalteu method (recalculated to chlorogenic acid). For the determination of total phenolic compounds, a spectrophotometric method using the Folin Ciocalteu reagent was applied. To 1 mL of plant extract, 1 mL of Folin–Ciocalteu reagent was added; after 3 minutes, 1 mL of 10% Na_2CO_3 was added, and the volume was adjusted to 10 mL with water. After 90 minutes, the optical density was measured at 725 nm. The obtained results are expressed as chlorogenic acid equivalents - mg/kg (Datuashvili, 2025).

Quantitative determination of catechins - by a spectrophotometric method: Extraction of the sample taken for analysis was carried out using 80% ethyl alcohol at a temperature of 70–75°C. From the total volume of the extract, 1 mL was taken, to which 3 mL of vanillin reagent was added, and after 3 minutes, the optical density of the red-colored sample was measured at 500 nm. As a control, 1 mL of the corresponding extractant and 3 mL of vanillin reagent were used. The obtained data were recalculated using a (+)-catechin calibration curve (Putkaradze, 2026).

Determination of antioxidant activity by the DPPH method: To determine total antioxidant activity, reactions proceeding via a radical mechanism are used, between a colored radical and an extract possessing antioxidant activity. The optical density of the solution is measured spectrophotometrically, allowing the evaluation of both individual substances and the total antioxidant activity of compounds. DPPH ($\text{C}_{18}\text{H}_{12}\text{N}_5\text{O}_6$, $M = 394.33$) is a free radical with maximum absorption at 515–517 nm. To determine antioxidant activity (radical scavenging activity), 3 mL of alcoholic DPPH solution was added to 1 mL of the analyzed extract, and after 30 minutes, the optical density of the test sample was measured at 515 nm. The control solution was 70% ethyl alcohol. The inhibition of free radical (DPPH) activity is calculated using the following formula: $\text{In}\% = (\text{AC} - \text{AS}) / \text{AC} \times 100$ (Datuashvili, 2025).

Identification of Compounds by Ultra-High-Performance Liquid Chromatography with a Mass Spectrometric Detector (UPLC-MS-PDA)

Identification of compounds by ultra-high-performance liquid chromatography with a mass spectrometric detector (UPLC-MS-PDA). For chromatographic analysis, the liquids obtained as a result of extraction were used. Before chromatography, the sample was prepared: from the total volume, 20 mL was taken for quantitative analysis, and the remaining part (150 mL) was concentrated. The obtained concentrate was filtered through a 0.45 μm membrane filter and transferred into so-called vials. For the identification and quantitative determination of catechins and other phenolic compounds, an ultra-high-performance liquid chromatography system Waters ACQUITY UPLC with a mass spectrometric detector (QDa, ESI) was used. Chromatographic analysis was performed on an ACQUITY BEH C18 column (2.1 $\times$ 100 mm, 1.7 μm). The mobile phase consisted of: eluent A – 0.1% formic acid in water, and eluent B – acetonitrile. Gradient elution was applied under the following conditions: 0–2.0 min – 5% B; 2.0–8.0 min – 20% B; 8.0–10.0 min – 35% B; 10.0–11.0 min – 95% B; 12.0 min – 5% B; 15.0 min – 5% B. The flow rate was 0.3 mL/min, the injection volume was 2 μL , and the column temperature was 40°C. Mass spectrometric detection was carried out in negative ionization

mode (ESI⁻). The applied parameters were: capillary voltage – 0.8 kV, cone voltage – 15 V, source temperature – 120°C, desolvation temperature – 500°C. Data acquisition was performed in SIR mode, with a scanning range of m/z 100–1000. For quantitative determination, a calibration curve with 5–7 points in the concentration range of 0.1–100 µg/mL was used, with a correlation coefficient ($R^2 \geq 0.995$).

Results and Discussion

Table 1. Quantitative determination of biologically active compounds of rhododendron and evaluation of their antioxidant activity.

Sampling site	collection	Extraction method	Phenols (mg/g dry weight)	Catechins (mg/g dry weight)	Amount of sample (mg) required for 50% inhibition of 0.1 Mm DPPH
Tskhmorisi		US bath	88,92	12,84	20,56
		US probe	59,65	8,00	41,23
Kharaula		US probe	81,12	18,00	19,65
		US bath	100,58	8,97	20,56
Machakhela		US probe	120,98	19,68	6,59

According to the research results, the total phenolic content in *Rhododendron ponticum* samples is relatively higher at the Machakhela location, particularly in the extract obtained by the US probe method (120.98 mg/g), while in other samples it ranges between 59.65–100.58 mg/g. The catechin content is also highest in the Machakhela sample (US probe) - 19.68 mg/g, followed by Kharaula - 18.00 mg/g, while in Tskhmorisi samples it is 12.84 mg/g (US bath) and 8.00 mg/g (US probe). According to antioxidant activity (IC₅₀), the highest activity was observed in the Machakhela sample (US probe) - 6.59 mg, while in other samples the values range between 19.65–41.23 mg, with the lowest activity recorded in the Tskhmorisi sample (US probe) - 41.23 mg. The obtained results indicate that Machakhela samples, particularly in the case of US probe extraction, are distinguished by both a high content of phenolic compounds and strong antioxidant activity.

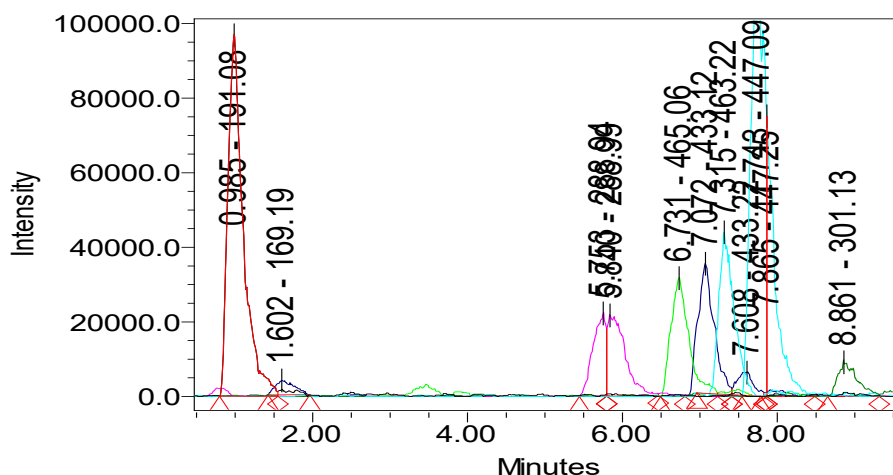


Figure 2. Chromatographic profile of phenolic compounds of rhododendron (*Rhododendron ponticum* L.) leaf extract (UPLC-MS analysis)

Table 1. LC-ESI-MS Markers – *Rhododendron ponticum* L.

Compound	RT (min)	m/z (ESI ⁻)	[M-H] ⁻	Fragments (MS/MS)	Compound Class
Quinic acid	0.985	191.08	—	—	Phenolic acid
Gallic acid	1.566	169	125	—	Phenolic acid
Quercetin-3-O-glucoside (Isoquercitrin)	7.269	463	301	—	Flavonol glycoside
Quercetin	1.098	301	179, 151	—	Flavonol aglycone
Kaempferol-3-O-glucoside	7.676	447	285	—	Flavonol glycoside
Catechin	5.897	289	245, 205	—	Flavan-3-ols
Epicatechin	6.161	289	179, 576	—	Flavan-3-ols
Procyanidin B-type	5.531	577	425, 289	—	Dimers

As a result of the study, quinic acid was identified in *Rhododendron ponticum* [M-H]⁻ m/z 191.08 (RT 0.985 min). In addition, catechin dimers, proanthocyanidins (Procyanidin B1, B2, B3) [M-H]⁻ m/z 577 (RT 5.531 min).

min) were detected. The following compounds were also identified: gallic acid $[M-H]^-$ m/z 169 (RT 1.566 min); quercetin-3-O-glucoside (isoquercitrin) $[M-H]^-$ m/z 301 (RT 1.098 min); quercetin $[M-H]^-$ m/z 191.08 (RT 0.985 min); kaempferol-3-O-glucoside $[M-H]^-$ m/z 447 (RT 7.676 min). Among flavanol compounds, catechin $[M-H]^-$ m/z 289 (RT 5.897 min) and epicatechin $[M-H]^-$ m/z 289 (RT 6.161 min) were detected, which indicates the high antioxidant activity of the plant.

Conclusion

As a result of the study, a high concentration of phenolic compounds was detected in the leaves of *Rhododendron ponticum* L., distributed in Adjara, which emphasizes the significant biological activity of this endemic species. Analysis conducted by ultra-high performance liquid chromatography with mass spectrometry detector (UPLC-MS-PDA) revealed phenolic compounds that provide high antioxidant activity of the plant, which is confirmed by the evaluation of DPPH radical inhibition and also demonstrates its potential as a source of natural antioxidants and a regenerative resource of bioactive components. The data presented in the table show that flavanol compounds (quercetin, kaempferol, catechins) and proanthocyanidins play an important role in the neutralization of free radicals, which emphasizes the potential of *R. ponticum* for medicinal and nutraceutical purposes.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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Author(s) Information

Salome Gogitidze

Batumi Shota Rustaveli State University
Ninoshvili av. 35, Batumi, Georgia.
Contact e-mail: salome.gogitidze@bsu.edu.ge
ORCID iD: <https://orcid.org/0009-0006-3690-8485>

Jeiran Futkaradze

Batumi Shota Rustaveli State University
Ninoshvili av. 35, Batumi, Georgia.
ORCID iD: <https://orcid.org/0009-0006-2566-6038>

Aleko Kalandia

Batumi Shota Rustaveli State University
Ninoshvili av. 35, Batumi, Georgia.
ORCID iD: <https://orcid.org/0000-0001-9570-9263>

Maia Vanidze

Batumi Shota Rustaveli State University
Ninoshvili av. 35, Batumi, Georgia
ORCID iD: <https://orcid.org/0000-0001-6754-6161>

Maia Kharadze

Batumi Shota Rustaveli State University
Ninoshvili av. 35, Batumi, Georgia.
ORCID iD: <https://orcid.org/0000-0001-6754-6161>

*Corresponding author(s) contact email

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Travel DNA: Persona-Driven Destination Prediction with Sentiment-Enhanced Hybrid Modeling

Busra Gedikoglu

Konya Technical University

Sait Ali Uymaz

Konya Technical University

Abstract: This study develops a sentiment analysis-based personalized travel destination prediction system using 12.57 million user reviews from the online accommodation platform Airbnb. The proposed system operates on a dataset covering 20 European cities through a five-stage pipeline: (i) data extraction and preprocessing, (ii) sentiment analysis with the multilingual transformer-based XLM-RoBERTa language model, (iii) traveler profiling with the K-Means clustering algorithm, (iv) trajectory mining with Markov chains, and (v) a three-signal hybrid prediction engine. The proposed hybrid architecture combines three signals: a Markov signal that models inter-city transition probabilities, a history signal reflecting users' revisit tendency, and a sentiment-city affinity signal that matches users' sentiment profiles with city characteristics. These signals are combined with weights optimized per traveler persona. In experiments conducted on 10,436 users (20.9% coverage rate) who reviewed during the test period and had travel history in the training period, the correct destination was found in the first recommendation (Hit@1) at 24.42%, in the top three (Hit@3) at 40.27%, in the top five (Hit@5) at 50.80%, and the Mean Reciprocal Rank (MRR) measuring ranking quality was 33.56%. Ablation study measuring each component's contribution reveals that the hybrid model outperforms all individual signals across every metric and that the proposed sentiment-city affinity signal achieves a 76% relative improvement in Hit@1 over the popularity-based baseline.

Keywords: Destination prediction, Sentiment analysis, Hybrid recommendation system, Persona-based recommendation, Markov chain

Introduction

With the growth of the digital sharing economy, online accommodation platforms such as Airbnb constitute a unique data source for understanding travel behavior. The millions of user reviews accumulated on these platforms contain travelers' emotional experiences, expectations, and satisfaction levels beyond numerical ratings. Bridges and Vásquez (2018) demonstrated that Airbnb reviews contain meaningful information despite the vast majority being positive. This rich textual data enables the development of sentiment-driven personalized prediction models beyond traditional recommendation systems.

Adomavicius and Tuzhilin (2005) categorized recommender systems into two primary paradigms: collaborative filtering (CF), which leverages preferences of similar users, and content-based filtering, which matches item features. However, the data sparsity problem in the travel domain significantly limits the effectiveness of CF methods. Meng et al. (2023) emphasizes the importance of evaluating context-aware approaches that incorporate additional information, such as time, location, and usage scenarios, into the model to overcome this limitation. Furthermore, traditional approaches fail to adequately model users' emotional experiences and sequential dependencies in travel trajectories. Sequential recommendation systems attempt to fill this gap by modeling temporal dependencies in users' action sequences. Quadrana et al. (2018) comprehensively reviewed methods in

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this area. Markov chains are widely used in travel trajectory prediction due to their low computational cost and interpretability advantages (Xu et al., 2022). However, these models also disregard traveler psychology and emotional compatibility.

In this study, to address the aforementioned gaps, a system called Travel DNA is proposed. The system extracts travelers' emotional profiles through multilingual sentiment analysis, identifies five distinct traveler personas via a clustering algorithm, and presents a three-signal hybrid prediction model with optimized weights for each persona. The main contributions of this study can be summarized as follows:

- (1) A large-scale multilingual sentiment analysis study on 12.57 million Airbnb reviews covering 20 European cities,
- (2) A sentiment-based profiling method that classifies traveler behavior patterns under five distinct personas,
- (3) Proposal of a signal designed in this study called Personalized Sentiment-City Affinity, demonstrating a 76% improvement in the Hit@1 metric over the popularity-based baseline,
- (4) Development of a three-signal hybrid prediction model with persona-specific weight optimization and validation through a comprehensive ablation study.

Related Work

Travel Recommendation Systems

Travel recommendation systems aim to predict future destination preferences based on users' past behavior. Collaborative filtering methods discover preferences of similar users through matrix factorization techniques (ALS, SVD) and k-nearest-neighbor algorithms (Adomavicius & Tuzhilin, 2005). However, CF methods suffer from degraded performance due to the data sparsity problem in the travel domain. Meng et al. (2023) provided a comprehensive review of context-aware recommender systems. Content-based approaches perform matching using destination features (price, location, facility type); however, they remain insufficient in capturing the emotional dimension of user experience.

Sentiment Analysis and Tourism

Advances in natural language processing, particularly transformer-based pre-trained language models, have enabled significant progress in sentiment analysis. The BERT model proposed by Devlin et al. (2019) established a new performance standard in text classification tasks. The XLM-RoBERTa model developed by Conneau et al. (2020) has been trained on over 100 languages, providing a strong foundation for multilingual sentiment analysis. In the tourism domain, sentiment analysis has been employed to improve demand forecasting performance with granular sentiment scores (Li et al., 2023) and to support deep learning approaches in personalized itinerary recommendation (Halder et al., 2024). However, the direct use of sentiment profiles for personalized destination prediction has been explored to a limited extent. This study distinguishes itself from existing work by designing a personalization signal that combines users' personal sentiment profiles with a city similarity matrix.

Sequential Recommendation Systems

Sequential recommendation systems model temporal dependencies in users' action sequences. Quadrana et al. (2018) comprehensively classified methods in this area. Markov chains are widely preferred in travel trajectory prediction due to their interpretability and computational efficiency (Xu et al., 2022). Rendle et al. (2010) achieved successful results in the next-basket prediction problem with factorized personalized Markov chains. Deep learning-based models have emerged prominently in recent years: GRU4Rec, proposed by Hidasi et al. (2016) in session-based recommendations, and SASRec, proposed by Kang and McAuley (2018), achieved high performance in sequential recommendations with an attention mechanism. In this study, the hierarchical Markov approach was preferred to maintain interpretability and produce stable predictions under limited data conditions.

Method

The proposed Travel DNA system consists of a five-stage pipeline: (i) data collection and preprocessing, (ii) multilingual sentiment analysis, (iii) traveler profiling, (iv) trajectory mining, and (v) hybrid prediction model. Each stage is described in detail in this section.

Dataset

The dataset consists of user reviews obtained from the Inside Airbnb (2025) project, covering 20 major European cities. Cities covered: Amsterdam, Barcelona, Berlin, Brussels, Budapest, Copenhagen, Dublin, Edinburgh, Florence, Lisbon, London, Madrid, Milan, Munich, Paris, Porto, Prague, Rome, Venice, and Vienna. A total of 12,570,926 reviews encompass 9,181,198 unique user profiles. Table 1 presents the basic statistics of the dataset.

Table 1. Dataset statistics

Feature	Value
Total Reviews	12,570,926
Unique Users	9,181,198
Number of Cities	20
Training Set (75%)	9,428,194
Validation Set (5%)	628,546
Test Set (20%)	2,514,186

Temporal split was used as the evaluation methodology: data was divided chronologically into 75% training, 5% validation, and 20% test sets. This approach prevents data leakage from future data into training (Quadrana et al., 2018). During prediction, only each user's history from the training period (last visited city) is used as input, and the first review in the test period is considered as the target.

Multilingual Sentiment Analysis

Sentiment analysis on review texts was performed using a model fine-tuned for sentiment classification on top of the XLM-RoBERTa base model developed by Conneau et al. (2020). XLM-RoBERTa is a multilingual transformer model pre-trained on over 100 languages, capable of processing reviews in European languages such as English, French, German, Spanish, and Portuguese without requiring translation. The model produces three categorical outputs—negative, neutral, or positive—and a confidence score for each review. These outputs were converted into a weighted sentiment score in the $[-1, +1]$ range by multiplying the category value (-1, 0, +1) by the confidence score. The resulting score captures the emotional direction and intensity of the user's experience in a particular city.

Traveler Profiling

A five-dimensional profile vector was constructed for each traveler: mean sentiment score, sentiment variability (standard deviation), mean price segment, number of unique cities visited, and logarithmic visit frequency. Price segments were defined in four categories based on room types in Airbnb listing data: shared room (0), private room (1), entire home/apartment (2), and hotel room (3). Users were divided into five distinct traveler personas using the K-Means clustering algorithm (Sinaga & Yang, 2020). The optimal number of clusters was determined by the elbow method. Table 2 shows persona definitions and their distributions in the test set. Persona names are interpretive labels assigned based on the behavioral characteristics of clusters and optimized signal weights.

Table 2. Traveler persona definitions

Persona ID	Persona Name	Number of Users (n)	Key Characteristic
P0	Single-City Traveler	813	Limited history, prediction from sentiment profile
P1	Variable Traveler	1,699	Inter-city transitions, loyalty significant
P2	Mainstream Traveler	7,287	Large mass, sequential transition patterns
P3	Predictable Traveler	578	High loyalty, revisit tendency
P4	Sequential Traveler	59	Sequential transition patterns dominant, highest Markov signal

Hierarchical Markov Chain

Inter-city transition probabilities were modeled with a hierarchical Markov structure. In transition mining, if the interval between two consecutive reviews of the same user was 21 days or shorter, these two cities were considered a connected travel transition; longer intervals were filtered as independent trips. Persona-based first-order transition matrices were constructed only for personas with multi-city visits (P1–P4); since the P0 (Single-City Traveler) group, by definition, has no inter-city transition data, no Markov matrix was generated for this persona. Predictions for P0 users are based on sentiment affinity and global popularity signals. During prediction, the system first consults the second-order Markov chain (last two-city pair), falls back to the persona-based first-order transition matrix when insufficient data is available, and ultimately falls back to the global popularity distribution. This hierarchical fallback mechanism prioritizes the most specific information available while addressing the data sparsity problem.

Hybrid Prediction Model

The proposed hybrid system combines three independent signals with persona-specific weights:

Hierarchical Markov Signal (Mk): Computes the transition probability of the next city based on the user's last visited city/cities. Produces stable predictions under data sparsity conditions through the hierarchical fallback mechanism.

Visit History Signal (Hi): Reflects the user's normalized visit frequency per city. This signal captures travelers' tendency to revisit specific cities (loyalty).

Personalized Sentiment-City Affinity Signal (Se): This is the core contribution of this study. Sentiment scores from the cities the user has visited are multiplied by the inter-city similarity matrix to produce affinity scores for cities not yet visited. The city similarity matrix was computed using cosine similarity from seven features: each city's mean sentiment score, sentiment standard deviation, proportional distribution of four price segments, and logarithmic visitor volume. Features were subjected to z-score normalization with StandardScaler to prevent different scale ranges from affecting the similarity computation.

The final prediction is computed as given in Equation (1):

$$\hat{P}(\text{city}|\text{user}) = w_1^{p^*} \text{Mk}(\text{city}) + w_2^{p^*} \text{Hi}(\text{city}) + w_3^{p^*} \text{Se}(\text{city}) \quad (1)$$

Here, p represents the persona index to which the user belongs, and the constraint $w_1^p + w_2^p + w_3^p = 1$ is satisfied. Weights were optimized separately for each persona via grid search on the validation set using the combined metric $(0.3 \times \text{Hit}@1 + 0.4 \times \text{Hit}@3 + 0.3 \times \text{Hit}@5)$. The search space was scanned with a step size of 0.05 in the $[0, 1]$ range for each weight, evaluating a total of 153 combinations that satisfied the constraint $w_1 + w_2 + w_3 = 1$.

Results and Discussion

Evaluation Metrics

System performance was evaluated using metrics widely adopted in the recommender systems literature (Adomavicius & Tuzhilin, 2005): Hit@k ($k=1,3,5$) measures the rate at which the actual destination appears in the top k elements of the generated recommendation list. NDCG@k (Normalized Discounted Cumulative Gain) evaluates ranking quality with logarithmic discounting. The Mean Reciprocal Rank (MRR) is defined in Equation (2), where $|U|$ denotes the total number of users and rank_i represents the position of the correct destination in the ranked list for user i .

$$\text{MRR} = (1/|U|) \sum 1/\text{rank}_i \quad (2)$$

For example, if the correct prediction is at the first position, it yields $1/1=1$; if it is at the third position, it yields $1/3 \approx 0.33$.

Ablation Study

An ablation study was conducted to measure the contribution of the hybrid model and each signal. In the ablation study, system components are disabled one by one to evaluate the impact of each component on performance. For this purpose, six different model configurations were compared. Table 3 presents the results. Table 3 presents the results of six model configurations evaluated on 10,436 test users. The results clearly demonstrate that the proposed hybrid model outperforms all individual signals and baselines across every metric. Particularly noteworthy is that the sentiment-city affinity signal proposed in this study (Hit@1=15.48%) achieves 76% relatively higher performance than the popularity baseline (Hit@1=8.80%) $((15.48-8.80)/8.80 \times 100 \approx 76\%)$. This difference confirms that sentiment-based personalization produces user-specific meaningful signals beyond merely following popularity. The history signal is the strongest individual signal in Hit@1 (24.24%); however, its growth rate slows in Hit@3 (32.13%) and Hit@5 (37.12%), falling behind the sentiment affinity signal (Hit@3=36.74%, Hit@5=46.95%). This indicates that the history signal is strong for the first prediction but insufficient for generating diverse recommendation lists. The sentiment affinity signal offers a more balanced performance profile. The proposed hybrid model achieves the highest performance across all metrics by combining these complementary strengths through a weighted linear combination.

Table 3. Ablation study results

Model	Hit@1 (%)	Hit@3 (%)	Hit@5 (%)
Random Baseline	5.30	15.89	26.63
Popularity Baseline	8.80	33.77	48.42
Markov Only	8.00	22.77	35.96
History Only	24.24	32.13	37.12
Sentiment Affinity Only	15.48	36.74	46.95
Hybrid Model (Proposed)	24.42	40.27	50.80

Overall Performance

The system achieved Hit@1=24.42%, Hit@3=40.27%, Hit@5=50.80%, NDCG@3=0.3352, NDCG@5=0.3782, MRR=33.56% on the test set. The Hit@5 value indicates that for more than half of the test users, the correct destination was among the top five recommendations. Additionally, multi-step trajectory prediction was evaluated: the system predicts two cities for each user, and the intersection rate (set-precision) between these predictions and the cities actually visited by the user is computed. Average set-precision was measured at 15.43% over 2,000 users.

Persona-Specific Analysis

Grid search optimization produced distinctly different weight distributions for each persona. Table 4 shows persona-based performance and optimized weights, where w_Mk, w_Hi, and w_Se denote the weights assigned to the Markov, visit history, and sentiment-city affinity signals, respectively.

Table 4. Persona-based performance and signal weights

Persona ID	Number of Users (n)	H@1	H@3	H@5	w Mk	w Hi	w Se
P0	813	100	100	100	0.05	0.10	0.85
P1	1,699	23.0	39.6	50.1	0.25	0.55	0.20
P2	7,287	13.9	31.5	43.7	0.40	0.45	0.15
P3	578	54.3	67.3	72.0	0.20	0.65	0.15
P4	59	27.1	54.2	61.0	0.65	0.25	0.10

The weight distributions offer valuable insights into the decision-making processes of different traveler types. For P0, sentiment affinity is the dominant signal (0.85), and these users having only a single-city history result in 100% accuracy. However, the impact of this trivial prediction mechanism on overall metrics should be considered: P0's share in the test set is 7.8% (813 / 10,436), and when P0 is excluded (n=9,623), Hit@1=18.03%, Hit@3=35.23%, Hit@5=46.64% are obtained. In mainstream travelers (P2), the balance between Markov (0.40) and history (0.45) reveals the importance of sequential patterns; in P3, history loyalty (0.65) reflects revisit tendency; and in P4, Markov dominance (0.65) demonstrates the deterministic role of sequential transition patterns. This differentiation demonstrates that persona-specific optimization is superior to uniform weights.

Discussion

Value of personalization: The sentiment-city affinity signal surpassing the popularity baseline by 76% in Hit@1 confirms that users' sentiment profiles carry tangible value for destination preference prediction.

Advantage of the hybrid model: The ablation study demonstrates that no single signal is the best across all metrics. The proposed hybrid model achieves the highest performance across all metrics by combining the complementary strengths of signals through weighted aggregation.

Limitations: The main limitations of the system are: (i) The dataset is limited to Airbnb only. (ii) The scope of 20 European cities is limited. (iii) Predictions cannot be generated for cold-start users; evaluation is restricted to users with training history (10,436 out of 50,000, coverage 20.9%). (iv) The P0 group's 100% accuracy stems from trivial predictions. (v) Comparison with SASRec (Kang & McAuley, 2018) and BERT4Rec (Sun et al., 2019) is left to future work. (vi) The CF signal was removed from the system due to negligible contribution.

Conclusion

In this study, the Travel DNA system was proposed for sentiment analysis-based personalized travel destination prediction using 12.57 million Airbnb reviews. The three-signal hybrid architecture (Markov + History + Sentiment Affinity) outperformed all individual signals and baselines across every evaluation metric (Hit@1=24.42%, Hit@5=50.80%). The proposed sentiment-city affinity signal achieved a 76% improvement in Hit@1 over the popularity-based approach, proving that sentiment analysis is a meaningful source of personalization for destination prediction. Persona-specific weight optimization strengthened the model's interpretability. Future work plans include comparison with deep learning-based sequential models, incorporation of additional signals such as seasonality and price dynamics, and scaling the system to broader city clusters.

Recommendations

Based on the findings of this study, future research directions are recommended: (i) Incorporating deep learning-based sequential models such as SASRec and BERT4Rec as additional baselines for performance comparison. (ii) Extending the dataset beyond Airbnb to include reviews from multiple platforms (e.g., Booking.com, TripAdvisor) for cross-platform generalizability. (iii) Integrating temporal features such as seasonality, holiday periods, and price dynamics into the prediction model. (iv) Developing a cold-start solution for users with no prior travel history by leveraging demographic or contextual features. (v) Scaling the system to a broader geographic scope including non-European destinations.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

* This study uses publicly available data from the Inside Airbnb project. No personally identifiable information was collected or processed. Ethics committee approval was not required as the study involves only publicly shared anonymous review data.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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Author(s) Information

Busra Gedikoglu

Konya Technical University
Department of Computer Engineering, Konya, Türkiye
ORCID iD: <https://orcid.org/0009-0009-1574-8576>

*Contact e-mail: e258229001018@ktun.edu.tr

Sait Ali Uymaz

Konya Technical University
Department of Computer Engineering, Konya, Türkiye
ORCID iD: <https://orcid.org/0000-0003-2748-8483>

*Corresponding author(s) contact email

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Experimental Determination of the Surface Energy of a Metal Composite Based on Crack Development Parameters

Valentina Kovaleva

Don State Technical University

Lyudmila Aref'eva

Don State Technical University

Abstract: The paper proposes and tests a method for measuring the surface energy of an alloyed steel with a fibrous ferrite-martensite composite structure. The method is based on the cleavage test and the measurement of the material's mechanical characteristics based on the development of a crack. The relationship between the material parameters, surface energy, and crack length was described in accordance with the Griffiths and Irwin fracture criteria, expressed through the invariant integral. The crack developed under flat deformation conditions with low values of the average radius of the plastic zone at the crack tip. In this case, the fracture mechanism is quasi-elastic or elastoplastic. Using analytical expressions for fracture criteria and experimental data on crack formation, the values of the surface energy of the steel composite were obtained. The results are in good agreement with known experimental data for single crystals of polymorphic iron modifications, which demonstrates the correctness and applicability of the proposed methodology. In the future, it will be possible to account for the delamination of ferrite during crack growth and, by determining the thicknesses of the ferrite and martensite layers, to determine their surface energies.

Keywords: Crack formation, Tensile strength, Ferritic-martensitic composite, Elastic-plastic deformation, Surface energy

Introduction

To ensure the safety and durability of materials, understanding the mechanical and thermodynamic factors of crack development is critical. The study of crack formation processes in composite materials is an important research area based on experimental data and a rigorous theoretical approach to their analysis (Shvechkov et al., 2020). The process of crack formation involves the simultaneous formation of two free surfaces. Griffiths was the first to analyze the relationship between mechanical characteristics and the surface energy of a solid. However, his model, which was confirmed by experiments, is only applicable to brittle amorphous bodies. Further development of the theory of material failure has allowed us to move from the description of brittle failure to failure under elastoplastic deformation (Astafiev, et al., 2001).

It should be noted that several well-known methods are used to experimentally determine the surface tension (energy) of solid metals, including the cleavage method, which is based on the Griffiths model and its modern interpretation. The surface energy of solids is a determining parameter not only in the mechanics of destruction, but primarily in all processes and phenomena occurring on the surface – adsorption, adhesion, cohesion, wetting, hydrophobicity of materials, sintering, etc. It depends on the temperatures of phase transitions, and therefore, on the technologies of processing materials. Today, theoretical approaches to determining the surface energy of solid crystalline bodies are being developed. However, there is a lack of experimental data on surface tension (energy) even for pure metals, and the data often have a wide range (Aref'eva, 2022). For alloys, such data is almost non-existent in both reference books and scientific literature. This highlights the need for a

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technically feasible method for measuring the surface tension (energy) of metals and alloys. As known, the Griffiths and Irwin criteria have been formulated for brittle fracture. A crack propagates when the released energy intensity or stress intensity factor reaches a critical value (Astafiev et al., 2001).

The critical values of the surface energy density of a body with a crack and the stress intensity factors are material constants that characterize its crack resistance under given external conditions, and they must be determined experimentally. The higher the values of these parameters, the better the material's resistance to crack growth and the higher the threshold for brittle failure. The failure of metals occurs with the formation of a zone of plastic deformation at the crack tip.

The energy of the localized field of plastic deformations significantly exceeds the surface energy of the formation of a new free surface. In this case, the application of Griffith's theory becomes incorrect. However, if the size of the plastic zone is small compared to the crack length, the failure of metals can often be considered quasi-brittle. The Griffiths criterion for brittle failure, formulated using the Ashby-Cherepanov-Rice invariant J-integral (Bondar et al., 2023; Chernavin et al., 2023), can be extended to include elastoplastic deformation.

The study focused on layered composites, which are characterized by a specific ratio of the volume fractions of their structural components and a discrete length of the reinforcing fiber. The aim of the work was to determine the surface energy of a metal composite using the Griffiths theory for elastoplastic deformation by determining the mechanical parameters of fracture.

Method

To obtain the mechanical parameters of fracture, the work carried out an analysis of the development of a crack of fatigue cyclic destruction of a composite material based on steel A414(F) with an oriented layered ferrite-martensite structure (Figure 1). The strict orientation of the phase structural components was obtained using a technological regime (Pustovoi et al., 2020, Egorov & Egorova, 2022) consisting of quenching from the intercritical temperature interval (730°C) followed by low-temperature tempering (200°C). The volume fraction ratio of ferrite and martensite was 70 / 30, respectively, and the length of the strengthening fiber was $l_{kp} = 160 \mu\text{m}$. (Duka & Aref'eva, 2025)

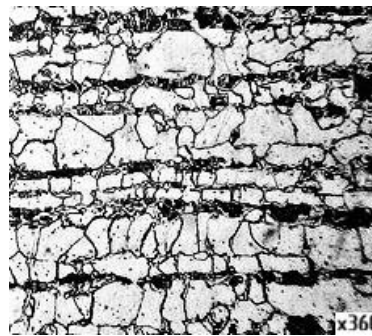


Figure 1. Microstructure of a ferrite-martensite composite based on A414(F) steel

A special installation was used to study the kinetics and mechanism of fracture. This installation was designed to induce a fatigue crack and study the kinetics of its development under cyclic loading (Pustovoi et al., 2020). The samples used for the study had a four-sided prismatic shape (10x10x100mm) with a pre-applied "U"-shaped concentrator ($r=0.25\text{mm}$, $\text{depth}=1.5\text{mm}$). To exclude the possibility of the crack banks hardening during its growth, the cyclic bending tests were carried out according to the non-zero loading cycle, in which the bending moment led only to tensile stresses arising in the sample, compressive stresses in this case were equal to zero.

The process of measuring crack growth was carried out by the method of potential difference. In the process of the crack growth, the dependence "potential difference - time" was automatically recorded. For the interpretation of the obtained data, a calibration graph was used, which connected the potential difference with the crack length. (Pustovoi et al., 2022; Gurdjiev et al., 2024). This graph was constructed based on the millivolt meter readings, taking into account the cross-section of the sample, the current value, and the crack length in Figure 2 (Pustovoi et al., 2022).

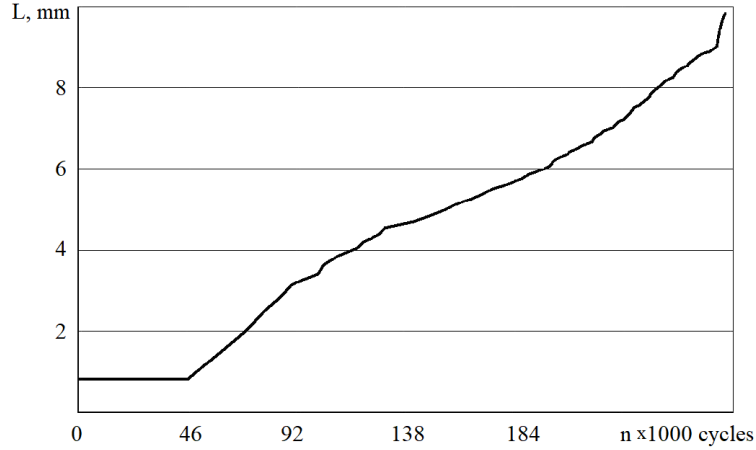


Figure 2. Dependence of crack length on the number of loading cycles in A414(F) steel

The relationship between the tensile strength σ , the crack length L , and the surface energy γ is expressed analytically using the Griffiths criterion

$$G = 2\gamma = \frac{K_I^2(1-\mu^2)}{E},$$

where μ is the Poisson's ratio and E is the modulus of elasticity.

Thus, the surface energy of a metal can be obtained from the experimental data of the crack length and the tensile strength:

$$\gamma = \frac{\pi(1-\mu^2)L\sigma^2}{2E}.$$

In the case of elastic-plastic deformation for a plane crack, the radius of the plastic zone is added to the half-length, expressed through the substance constants and the yield strength (Babeshko et al., 2022).

Results and Discussion

Earlier in the work of Pustovoit with co-authors (Pustovoit et al., 2022; Pustovoit et al., 2023) it was established that the growth of a crack occurs in steps, i.e. in the process of cyclic loading of the sample, first a zone of plastic deformation of the metal arises, and after the accumulation of stresses of a certain magnitude in it, their relaxation occurs in the form of the occurrence of a crack and its jump-like growth. Sliding occurs in the $\{110\}$ and $\{112\}$ planes, and the effective length of the sliding line is quite long, which leads to the rapid formation of flat dislocation clusters at the ferrite-martensite interphase boundary, local overstressing in this area, the formation of a crack nucleus, and the destruction of the martensitic layer. Based on the data from the above-mentioned work, the surface energy of A414(F) steel with a ferrite-martensitic structure was calculated.

The average radius of the plastic zone at the crack tip is small in relation to the total crack length and is 3.8 mm. The value of the surface energy was obtained for two cases of fracture mechanisms: brittle (ideal, used for comparison) and elastoplastic (real). In our calculations, the delamination of the ferrite phase was not taken into account. It should be noted that the results are obtained at room temperature, as the crack development occurred in steel without heating. In the first case, the surface energy value is 1308 mJ/m², and in the second case, it is 1949 mJ/m².

Our results were compared with known experimental data that were recommended as reference data. The surface energy of α -iron for the (110) face is 1480 mJ/m², γ -iron for the (100) and (111) faces is 2145 and 1370 mJ/m², δ -iron for the (110) face is 1407 mJ/m², and for a polycrystal is 1624 mJ/m² (Schönecker, et al., 2015). The surface tension of γ - and δ -iron was determined using the "zero" creep method and is 2170±330 and 2320±80 mN/m, respectively (Schönecker et al., 2015).

Conclusion

The work performed measurements of the surface tension of the alloyed steel A414(F) by a method similar to the cleavage method and based on the measurement of the crack length in the composite material. The analytical relationship between the material parameters, surface energy and crack length were described in accordance with the Griffiths and Irwin criteria of fracture, expressed through the Ashlby-Cherepanov-Rice integral. The established averaged radius of the plasticity zone under plane deformation allows us to consider the considered mechanism of destruction to be quasi-elastic or elastoplastic and to apply the above criteria for assessing the surface energy.

From the analysis of the results obtained, it can be concluded that the proposed and tested technique allows for a good accuracy to determine the value of the surface tension of a polycrystalline material and, in particular, is applicable to composites with a fibrous structure. It is possible that in the future, by taking into account the delamination of ferrite during crack development and knowing the thickness of the phase layers, it will also be possible to estimate the surface energy of ferrite and martensite.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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Author(s) Information

Valentina Kovaleva

Don State Technical University

Rostov-on-Don, Russia

ORCID iD: <https://orcid.org/0000-0001-7266-7224>

*Contact e-mail: valentina.duka.92@mail.ru

Lyudmila Aref'eva

Don State Technical University

Rostov-on-Don, Russia

ORCID iD: <https://orcid.org/0000-0003-2431-6897>

*Corresponding author(s) contact email

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Evaluation of Konya Selçuklu Canyon Park Landscape Design Using Eye Tracking Technique

Ruhugul Ozge Gemici
Selçuk University

Abstract: Eye-tracking technology is a method that provides qualitative and quantitative results by monitoring pupil movements with the aid of infrared rays. In this study, visual perception and behaviors regarding the landscape design of Konya Selçuklu Canyon Park were evaluated through the eye-tracking method with the participation of volunteers. In this context, images obtained from the research area were shown to 28 participants using eye-tracking technology. In the study, Areas of Interest (AOIs) were defined as landscape components (plants, urban furniture, and pavements). Based on these defined areas of interest, heatmaps and eye-tracking metrics (average fixation duration and fixation count) were obtained through eye-tracking software. Repeated Measures ANOVA analysis was performed using the data obtained from the eye-tracking metrics. The findings revealed statistically highly significant differences between the landscape components in terms of both eye-tracking metrics ($p < 0.001$). It was determined that participants showed the highest visual interest in plants (61.68 units; 3.48 sec), followed by urban furniture (20.79 units; 3.20 sec), while pavements received the lowest visual interest (16.25 units; 1.42 sec). Bonferroni-corrected pairwise comparison (post-hoc) tests showed that plants significantly differed from all other landscape components in terms of fixation count, while they had similar values to urban furniture in terms of average fixation duration. This situation indicates that plants play an "attention-grabbing" role, while urban furniture undertakes an "information processing" role. Pavements, which received the lowest visual interest in both metrics, ranked at the bottom of the visual hierarchy.

Keywords: Eye-tracking technology, Konya Selçuklu Canyon Park, Landscape design, Visual behavior, Visual perception.

Introduction

Eyes, being one of the sensory organs, are the window to the mind and hold a very important place in our perception of the world. Therefore, the eye-tracking technique is one of the methods used for understanding the processes occurring in the mind through the tracking and recording of eye movements (Çağiltay, 2011).

Eye-tracking technology is a useful tool that provides objective insights for researchers and scientists who wish to examine human behaviors. The close relationship between eye movement and human behaviors has made this technique a reliable method through which individuals' eye movements can be measured. Thus, the eye-tracking method has enabled the observation of where a person is looking at any given time and the sequence of their eye movements (Coşkun, 2019).

The concept of landscape has a broad scope that expresses all natural and cultural, living and non-living components on earth, and incorporates all possible definitions thereof (Orgin, 1998; Çelik, 2004). According to the European Landscape Convention, landscape denotes an area, as perceived by people, whose character is the result of the action and interaction of natural and/or artificial factors (Simensen et al., 2018).

Landscape design, which is the field of study of landscape architecture at sub-scales, is the process in which the outdoor space is shaped in line with planning decisions. In landscape design, the use of the site is established according to needs. The main goal in this process is the creation of the best possible spatial composition regarding the study area within the context of sustainability and in the light of design principles. Attributes such as the designer's vision, cultural background, and aesthetic understanding allow for the production of an infinite number of solutions in landscape design (Korkut et al., 2010).

The primary objective of this research, in which the eye-tracking method—one of the neuroscientific data collection techniques—is used, is to evaluate the visual perception and behaviors regarding the landscape design of Konya Selçuklu Kanyon Park through volunteer participants. Within the scope of the research process; first, a literature review on the subject was conducted, and then, by performing fieldwork, high-resolution representative photographs best reflecting the landscape character of the study area were obtained from the site. Additionally, interviews about the site were held with officials working at Selçuklu Municipality prior to the eye-tracking experiments. After the eye-tracking experiments were carried out, the eye-tracking data (average fixation duration and fixation count) were converted into numerical data via Tobii Pro Lab and subjected to statistical analysis. In light of these findings, the landscape design of Konya Selçuklu Kanyon Park was evaluated using the eye-tracking method, and conclusions and recommendations were developed in line with the data achieved.

Materials and Methods

Study Area

Konya Selçuklu Kanyon Park is located in the Selçuklu district of Konya province, Türkiye. Selçuklu is one of the central districts of Konya province (Figure 1). The Selçuklu district was established on the plain, which is a lakebed, and the Takkeli and Loras mountains are located to its west. It has an arid climate; therefore, summers are hot and dry, and winters are cold and rainy (Anonymous, 2026a).

The reasons for choosing Konya Selçuklu Kanyon Park as the study area are that it constitutes a successful example of the recreational reclamation (rehabilitation) of areas degraded as a result of anthropogenic activities (mining) and that the visual perception hierarchy in areas with such extreme topography has not been previously analyzed using the eye-tracking method.

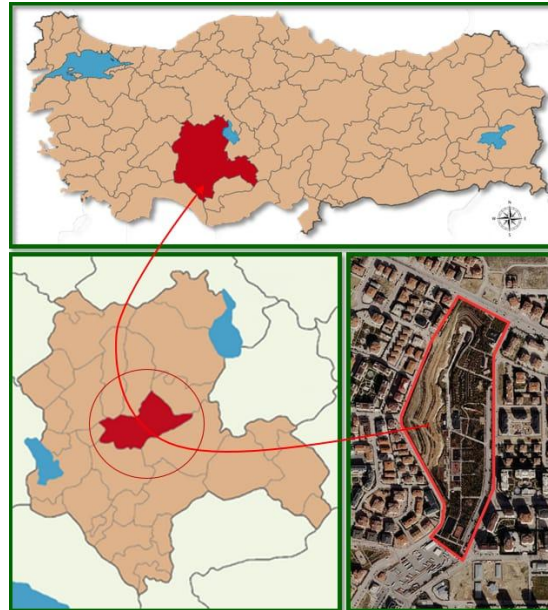


Figure 1. Location and plan of Konya Selçuklu Kanyon Park (Google Earth, 2026)

The study area, located within the borders of the Yazır Neighborhood of the Selçuklu district, was transformed into a neighborhood park through the rehabilitation of an idle site previously used as a stone quarry. This characteristic area, through which an active fault line passes, was designed after the termination of stone quarrying activities and opened for service under the name of Konya Selçuklu Kanyon Park with a total surface

area of 122,500 m². While designing the landscape of the area, it was aimed to create a multi-functional recreation area including resting, entertainment, and sports activities. At the end of the landscape planning and design processes, the area was created as a functional landscape area that both preserves its natural features and responds to the needs of the users. In this direction, the park was presented to the public as a social and recreative space where local people can spend their leisure time by getting away from their daily routines (Anonymous, 2026b).

Stimuli

Static landscape images collected from the study area were used as stimulus material in the eye-tracking experiment. As emphasized in the literature (Liu et al., 2022; Jiang et al., 2017), landscape images provide an effective alternative for on-site environmental assessments. During the photo shoots, care was taken to determine the viewpoints that best reflect the landscape design and user perception of the area. A total of 40 images were obtained from the field. The images were standardized in terms of size and color tolerance using Adobe Photoshop software. Considering the areas where visitors spend the most time in the site, it was decided to use 8 high-resolution photographs in the eye-tracking studies (Figure 2).

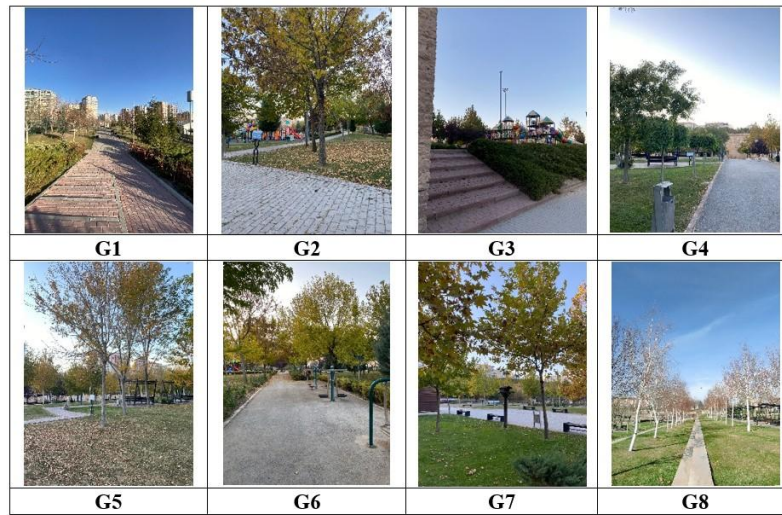


Figure 2. Selected experimental images (Original, 2025)

Selection of Participants

In academic research conducted using eye-tracking devices, determining the optimum sample size is of great importance in order to reach qualified data. In this direction, power analysis must be performed to ensure the success and statistical validity of the study. In eye-tracking experiments, the process of participants using the device individually and sequentially extends the duration, which reveals the necessity of efficient use of research resources. For this reason, the minimum sample size required to reach the targeted statistical power was calculated using G*Power software (v3.1.9.7).

In the study, a single-factor, within-subjects design consisting of three levels (plants, urban furniture, and pavements) was used to evaluate visual behaviors toward different landscape components. In the preliminary power analysis conducted to guarantee statistical power, parameters of medium effect size ($f = 0.25$), $\alpha = 0.05$ significance level, and 0.8 power value were used. According to these parameters, the minimum sample size required for one-way repeated measures ANOVA analysis was determined as 28.

The research included 32 individuals consisting of volunteer undergraduate and graduate students and faculty members from the Department of Landscape Architecture at Selçuk University. It was confirmed that all participants had normal or corrected-to-normal visual acuity and normal color vision. During the data cleaning process, 5 participants exhibiting low data quality, excessive blinking, or eye movements incompatible with device calibration were excluded from the analysis. The final analyses were performed with data obtained from a total of 28 participants (18 females, 10 males) ranging in age from 20 to 50.

Experimental Equipments

In order to collect eye-tracking data in the study, a screen-based Tobii Pro Nano (Tobii Technology AB, Sweden) eye-tracking device with a 60 Hz sampling rate was used. Data recording and visualization processes are carried out through Tobii Pro Lab (Full Edition v1.171) software. Visual stimuli were shown to the participants via a 15.6-inch laptop monitor with a resolution of 1920×1080 pixels.

G*Power (v3.1.9.7; Heinrich Heine University, Düsseldorf, Germany) software was utilized in calculating the sample size. Statistical analyses were performed using SPSS 27.0 (IBM Corp., Armonk, NY, USA) software. Adobe Photoshop 2021 (Adobe Inc., San Jose, CA, USA) and AutoCAD 2022 (Autodesk, USA) software were used during the preparation, standardization, and technical drawing stages of visual materials. Current satellite images and location data of the research area were obtained through the Google Earth (Google LLC, Mountain View, CA, USA) platform based on the location of Konya, Türkiye.

Experimental Procedure

The eye-tracking study was conducted individually in a controlled environment isolated from external factors (weather conditions, etc.) (Gao et al., 2021; Cottet et al., 2018; Amati et al., 2018). Prior to the experiment, participants were provided with detailed information regarding the experimental procedure and their ethical rights, followed by the acquisition of their written consent via the "Volunteer Informed Consent Form." Participants were positioned in front of the laptop, to which the eye-tracking device was integrated, ensuring an optimum distance of approximately 65 cm from the screen. A 9-point calibration procedure was applied to verify measurement accuracy, and validation values below 0.50 were accepted as successful.

During the experimental phase, 8 landscape images, each presented for a duration of 5 seconds, were shown to the participants. This duration was determined in accordance with similar methodological approaches in the literature (Dupont et al., 2016; Dupont et al., 2015). To ensure that participants perceived the landscape in the most natural way, no guidance was provided, and they were allowed to perform "free viewing" (Huang & Lin, 2019; Berto et al., 2008). Throughout the experiment, the physical health, safety, and confidentiality of the personal data of the participants were meticulously protected. The research protocol was approved by the Scientific Ethical Evaluation Board of the Faculty of Architecture and Design at Selçuk University on November 13, 2024, and full compliance with the principles of the Declaration of Helsinki was maintained throughout the process.

Eye-Tracking Metrics and Definition of Areas of Interest (AOI)

In this research, a multi-indexed collaborative study was conducted using fixation count (FC), average fixation duration (AFD), area of interest (AOI), and heatmaps to reveal the visual perception and behaviors of participants toward the landscape design of Konya Selçuklu Kanyon Park (Table 3.1). Fixation count refers to the amount of fixation a participant makes on a specific region and is informative in examining the participant's interest or the ease of understanding information (Tullis & Albert, 2013). Fixation duration reflects the level of interest and the depth of cognitive processing in a specific region; this metric is frequently used in evaluating subjective preference and satisfaction (Negi & Mitra, 2020). Average fixation duration is calculated by dividing the total fixation duration in a defined area by the fixation count (Xue & Zhu, 2024). An increase in the average fixation duration indicates greater targeted interest and engagement toward a region (Poole and Ball, 2006).

Before the participants were included in the eye-tracking experiment, the selected landscape images were first uploaded to the eye-tracking software. Subsequently, Areas of Interest (AOI) were created on these images transferred to the software. AOIs refer to specific regions in the stimulus space considered important and relevant for the experimental design of the study (Orquin et al., 2015). In the context of monitor-based eye tracking, these areas are generally defined by screen pixel boundaries. In the study, plants (trees, shrubs, flowers, and groundcover plants), urban furniture (equipment elements such as benches, trash cans, camellias, sports equipment, and children's playgroups), and pavements (walking paths and floor coverings) were determined as areas of interest. In this study, AOI boundaries were meticulously defined to follow the outer contour of each landscape component using the manual marking tools in the Tobii Pro Lab interface. To account for oculomotor bias, AOI boundaries were expanded one mm beyond the actual areas analyzed. The software then used a specific algorithm to assign gaze points to the relevant AOIs (Benjamins et al., 2018). Heatmaps, on the other hand, were created by overlapping and visualizing all fixation counts and durations obtained from the participants using the Tobii Pro Lab software.

The creation of areas of interest is a methodological necessity for obtaining eye-tracking metrics from the eye-tracking software. These marked areas of interest pertain to the pre-experimental process, and participants do not see these markings during the experiment.

Data Analysis Methods

The eye-tracking data were processed by filtering using the Tobii I-VT fixation filter, which aims to exclude fixations in raw data. In the context of Tobii Pro Lab software, this filter includes a comprehensive set of procedures to define fixations. The procedural steps within the scope of the Tobii visualization infrastructure and the Tobii fixation filter include gap filling, eye selection, velocity calculation, I-VT classification, merging adjacent fixations, and discarding short fixations (Olsen & Matos, 2012). After the data were prepared and processed according to the specified criteria, statistical analyses were performed to examine the relationships between eye movement patterns and other variables of interest. To ensure data quality, samples with an eye movement sampling rate higher than 90% were selected for the analysis process (Ouzts and Duchowski, 2012). This criterion assists in providing accurate information regarding the visual behavior patterns of the participants while increasing the reliability of the data used in the study. Within the scope of statistical analyses, first, the mean values (M) and standard deviation (SD) values of the eye-tracking data (average fixation duration and fixation count) of the participants across all images were obtained. Subsequently, to test the statistical significance of the differences between the areas of interest (plants, urban furniture, pavements), Repeated Measures ANOVA analysis was performed separately for both 'average fixation duration' and 'fixation count' metrics.

In the analyses, the assumption of sphericity of variance was checked with Mauchly's Sphericity test; in cases where this assumption was not met, the Greenhouse-Geisser correction was taken into account depending on the epsilon value. Bonferroni-corrected Post-Hoc pairwise comparison tests were performed to determine between which categories significant differences occurred. In all statistical evaluations, the significance threshold was accepted as $p < 0.05$.

Results

Creating Eye-Tracking Heat Maps

Within the scope of the research, a qualitative visual analysis was conducted based on the participants' fixation locations, counts, and durations on the landscape images. The total fixation data obtained from 28 participants were aggregated through Tobii Pro Lab software to produce 8 heatmaps (Figure 3).

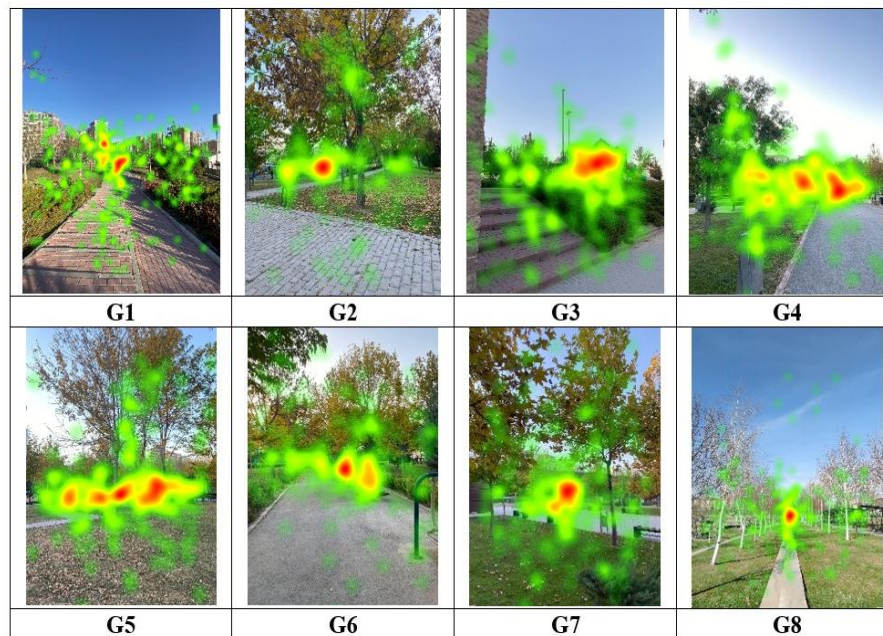


Figure 3. Heat maps (Output from Tobii Pro Lab)

The color scale used in the heatmaps expresses the intensity of visual attention. In this direction, red-colored areas represent the highest intensity fixations, while yellow and green-colored areas represent the lowest intensity fixations. This intensity distribution in the heatmaps visually reveals the perceptual hierarchy between plants, urban furniture, and pavements within the park.

Qualitative examinations conducted via heatmaps reveal that visual focal points vary depending on the stimulus content. Accordingly, it was determined that the participants' attention primarily concentrated on urban furniture in images coded G1, G2, G3, and G6. In contrast, it is observed that plants stand out as the dominant visual stimuli in images coded G4, G5, and G7. In the image coded G8, unlike the other images, visual interest was found to be on the pavements. This distribution shows that the position and visual salience of landscape components within the composition directly affect the scanning strategies of the users.

Descriptive Statistics of Eye-Tracking Metrics

In the first stage of the statistical analyses, the arithmetic mean (M) and standard deviation (SD) values for the metrics of fixation count and average fixation duration were calculated for each area of interest (AOI). These data provide a comprehensive preliminary assessment of visual behaviors across landscape components. The data obtained from the eye-tracking experiment conducted on the landscape components show that participants directed the highest fixation toward plants, followed by urban furniture and pavements (Table 1).

Table 1. Descriptive statistics

Landscape Components	Eye tracking Metrics	Mean (M)	Standard Deviation (SD)
Plants	Fixation Count	61,68	14,94
	Average Fixation	3,48	0,79
	Duration (s)	20,79	7,16
Urban Furniture	Fixation Count	20,79	7,16
	Average Fixation	3,20	1,18
	Duration (s)	16,25	6,36
Pavements	Fixation Count	16,25	6,36
	Average Fixation	1,42	0,66
	Duration (s)		

Assumptions of Statistical Analysis

The equality of variance-covariance matrices, which is one of the fundamental assumptions for the validity of the repeated measures ANOVA analysis, was controlled with Mauchly's Test of Sphericity. This test determines whether the data meet the necessary mathematical prerequisites for ANOVA analysis by answering the question, "Are the differences between error variances equal?"

Table 2. Mauchly's test of sphericity results regarding eye-tracking metrics

Eye Tracking Metrics	Mauchly's W	Approx. Chi-Square (χ^2)	Degrees of Freedom (df)	p-value
Fixation Count (FC)	0,912	2,415	2	0,284
Average Fixation Duration (AFD)	0,875	3,120	2	0,162

When Table 2 is examined, it is seen that the Mauchly's test of sphericity results for both fixation count ($W = 0.912$; $p = 0.284$) and average fixation duration ($W = 0.875$; $p = 0.162$) metrics are not statistically significant ($p > 0.05$). These findings show that the assumption of sphericity is met and the data are suitable for repeated measures ANOVA analysis. Since the assumption was verified, there was no need for a Greenhouse-Geisser or similar correction coefficient.

Evaluation of Visual Behaviors across Landscape Components

In the research, since the same group of participants examined all visual stimuli, Repeated Measures ANOVA analysis was performed instead of standard ANOVA to determine the differences between groups. The primary objective of this analysis is to identify whether the landscape components consisting of plants, urban furniture, and pavements show a statistically significant difference in terms of fixation count and average fixation duration.

Table 3. Repeated measures ANOVA results regarding eye-tracking metrics

Eye Tracking Metrics	Degrees of Freedom (<i>df</i>)	F-value	p-value	Effect Size (η^2_p)
Average Fixation Duration (AFD)	(2, 54)	48,12	< 0,001 *	0,64
Fixation Count (FC)	(2, 54)	148,32	< 0,001 *	0,84

*Significant level 99.9 % ($p < 0.001$)

The repeated measures ANOVA results reveal that the examined landscape components (plants, urban furniture, and pavements) created a statistically highly significant effect on the participants' visual behaviors ($p < 0.001$) (Table 3). The analysis findings confirm that highly significant differences were detected in terms of both fixation count ($F(2, 54) = 148,32$; $p < 0,001$; $\eta^2_p = 0,84$) and average fixation duration ($F(2, 54) = 48,12$; $p < 0,001$; $\eta^2_p = 0,64$) metrics.

These data show that the type of landscape component has an explanatory power of 84% over the variability in participants' fixation counts and 64% over the variability in average fixation durations. The high effect size (η^2_p) values obtained prove that different landscape components play a non-random, systematic, and decisive role in the participants' visual behaviors. Consequently, the quality of the material used in landscape design has been identified as a fundamental variable that directly shapes the user's way of perceiving the space and visual focusing strategies.

Pairwise Comparisons of Landscape Components

A separate Repeated Measures ANOVA analysis was conducted for each eye-tracking metric (AFD and FC). Following the detection of statistical significance at the $p < 0.001$ level in the analysis results, Bonferroni-Corrected (Post-Hoc) pairwise comparison tests were applied to determine which landscape component established dominance as a visual stimulus and to identify specific variations between groups. The test results are presented in Table 4. The obtained findings revealed significant differences and some perceptual similarities between landscape components for both eye-tracking metrics.

Table 4. Post-Hoc (Bonferroni-Corrected) pairwise comparison test results

Eye tracking Metrics	(A) Group	(B) Group	Mean Difference (A-B)	Standard Error	p-value
Fixation Count (FC)	Plants	Urban Furniture	40,89*	2,45	< 0,001
	Plants	Pavements	45,43*	2,82	< 0,001
	Urban Furniture	Pavements	4,54	1,98	0,082
Average Fixation Duration (AFD)	Plants	Urban Furniture	0,28	0,14	0,154
	Plants	Pavements	2,06*	0,22	< 0,001
	Urban Furniture	Pavements	1,78*	0,19	< 0,001

*Significant level 99.9 % ($p < 0.001$)

Pairwise comparisons for the fixation count metric indicate that plants achieved a statistically highly significant superiority compared to other landscape components ($p < 0.001$).

- Plants received an average of 40.89 more fixations than urban furniture and 45.43 more fixations than pavements. This situation confirms that plants are the primary visual stimuli in landscape design.
- The difference in fixation count between urban furniture and pavements ($p = 0.082$) remained above the significance threshold (0.05) and did not show a statistical difference. This finding reveals that participants fixated on these two components with similar frequency.

The pairwise comparison results for the average fixation duration metric are as follows:

- The difference in average fixation duration between plants and urban furniture was not found to be statistically significant ($p = 0.154$). This result indicates that although plants are noticed visually faster, once participants fixate, they examine urban furniture with a cognitive process as long as that of plants.
- Pavements were examined for a significantly shorter duration compared to both plants (2.06 s difference, $p < 0.001$) and urban furniture (1.78 s difference, $p < 0.001$). This situation reveals that the visual attention-grabbing potential and cognitive processing depth of pavements are at the lowest level.

Discussion

The eye-tracking data obtained in the study reveal that landscape components create a statistically highly significant hierarchy in user perception. The high effect size in the analysis results confirms that the primary variable governing visual attention is directly the quality of the landscape components.

The fact that participants reached the highest total fixation count and duration on plants strongly supports the "Biophilia" (Wilson, 1986) hypothesis in the literature. According to visual perception mechanisms, artificial elements such as urban furniture have the potential to attract instantaneous attention thanks to the form and texture contrast they create with their surroundings. This situation also explains the local concentrations in the heatmaps. Indeed, Amati et al. (2018) state that the human eye shows high sensitivity toward artificial elements even if they occupy a small part of the scene. However, in this study, the fact that plants received the highest values in terms of both count and duration indicates that natural elements create not just an instantaneous arousal, but a sustainable cognitive interest in the human mind.

Humanity's evolutionary predisposition toward natural elements ensures that these components are processed more deeply in cognitive processes and that attention is fixed at this point for a long duration (Ulrich, 1983). This situation scientifically proves that while artificial elements are stimuli perceived quickly, natural elements are spiritual and restorative components focused on for long periods. These highly significant differences confirm that the function of plants in recreation areas goes beyond being an aesthetic background and serves as a fundamental primary focal point guiding spatial perception. This finding is consistent with Kaplan's (1989) "Attention Restoration Theory," revealing that plants are the primary stimuli initiating the mental restoration process.

Although urban furniture lags behind plants in terms of fixation count, it shows similar values to plants in terms of average fixation duration. This situation reveals that the functional details, ergonomic forms, and structural features of urban furniture trigger a more intense cognitive processing in the participants. In other words, it is confirmed that equipment elements are not seen by the user merely as objects, but that these components are spatially analyzed in depth. This result proves that equipment elements are perceived as 'action points' in recreation areas and that users examine these areas in detail not just to look at them, but to analyze their usage potential.

The fact that pavements received the lowest values in both metrics indicates that floor coverings play a passive role in the space. The low fixation values reveal that participants did not feel the need to keep their gaze on the pavements and perceived these surfaces as a visual plane creating a low cognitive load.

Limitations and Future Research

Although this study provides important insights into visual perception and behavior in recreation areas, it includes several limitations. First, the fact that the sample group largely consists of landscape architecture students and academics carries a risk of "expert bias." The visual scanning strategies and aesthetic preferences of individuals with design education may differ significantly from others. This situation, combined with the limited sample size, may restrict the external validity and generalizability of the findings to the general public. Therefore, for future research, it is recommended to increase the sample size and include a more heterogeneous participant population with diverse professional and educational backgrounds.

Second, this research was conducted solely using eye-tracking data. Future studies could adopt a "mixed-method" approach where these data are supported by research methods such as surveys or interviews. Examining the correlation between eye-tracking data and participants' subjective preference and satisfaction surveys would simultaneously reveal both the cognitive and psychological dimensions of the perception toward landscape components.

Third, this study was carried out using static stimuli at a specific point in time. However, landscape areas are in a state of continuous change over time. Future research could investigate the phenological cycles of plants (foliated/non-foliated periods) and different seasonal characters, as well as the effects of artificial lighting conditions, such as night lighting, on urban furniture and spatial hierarchy. Such variable-oriented approaches would provide comprehensive contributions to literature in terms of understanding the perceptual performance of landscape components under dynamic environmental conditions.

Finally, in addition to eye-tracking data, other biometric measurements such as Galvanic Skin Response (GSR) or EEG could be included in the study to more comprehensively examine the stress-reducing and restorative effects of landscape components on users.

Conclusion and Recommendations

This study, through the example of Konya Selçuklu Kanyon Park, has empirically revealed the visual perceptions and behaviors of users toward landscape design components in urban recreation areas via eye-tracking technology. The eye-tracking data obtained from volunteer participants have demonstrated that landscape design components are not only aesthetic elements but also create a measurable visual hierarchy. The data obtained are of strategic importance for making sense of the local landscape identity specific to Konya and for creating an evidence-based basis for future design decisions. The fundamental conclusions reached as a result of the research are presented below:

- Plants are not just complementary aesthetic elements in recreation areas; they are primary focal points that establish the visual hierarchy, dominate attention, and spatially guide the user experience.
- Urban furniture components are critical design elements that are subjected to an in-depth information processing process due to their functional details and ergonomic forms, beyond being elements merely noticed superficially by users.
- Pavements, occupying the lowest step of the visual hierarchy, serve a function that brings components on the vertical plane (plants and equipment) to the fore and provides continuity to the space.
- The statistically proven perceptual differences have methodologically confirmed that landscape design can now be evaluated based on measurable cognitive evidence obtained through biometric methods such as eye-tracking, rather than only intuitive approaches.

In light of the findings obtained within the scope of this research, the recommendations developed for future landscape design applications are presented below:

- In urban areas like Konya, where continental climate and structural elements are dominant, green space continuity and visual accessibility to these areas should be addressed as a fundamental design parameter for the psychological restoration and visual comfort of users. The biometric data obtained specifically for Konya Selçuklu Kanyon Park prove that the density of plant material is directly proportional to the level of visual fixation and increases spatial quality. In this context, strengthening the urban green infrastructure by disseminating recreation areas in the Kanyon Park typology throughout Konya is a strategic necessity for a sustainable urban life.
- The high fixation count of plants reveals that these elements should be positioned especially at park entrances and orientation points in accordance with the principle of emphasis. At these strategic points, choosing species that contrast with the environment in terms of form, color, or texture (for example, coniferous or species with striking flowering characteristics) will strengthen the visual hierarchy. The high number of fixations also shows that the eye performs a dynamic scanning movement within the space. To balance this visual mobility, a rhythm can be created through the repetition of similar plant groups at certain intervals. This rhythmic design will allow the user to carry their visual attention throughout the space without creating cognitive fatigue and to perceive different parts of the park within a holistic continuity.
- The high average fixation duration of plants confirms that users not only notice these vertical elements but also examine them in an in-depth and detailed manner. In line with this finding, a quantitative increase in green space should not be the only goal in landscape designs; qualified compositions based on the principle of plant diversity, offering different heights, textures, forms, and seasonal color transitions, should be designed. The use of species adapted to the local climate within this diversity should be handled not only as an ecological necessity but also as a strategic element of local landscape identity that extends the user's dwell time in the space and maximizes their perceptual satisfaction.

- The similarity of the average fixation duration of urban furniture with that of plants confirms that in the park usage culture in Konya, equipment is not just a functional fixture but also an aesthetic object analyzed in depth. Therefore, material quality, ergonomics, and richness of visual detail should be prioritized in the selection of equipment elements such as benches, lighting, and trash cans. Original urban furniture designs reflecting the local landscape identity, containing Seljuk motifs or a modern-local synthesis, will strengthen the cognitive bond and sense of belonging that users establish with the space.
- The characteristic topographical structure of Kanyon Park (canyon form) naturally increases the visual salience of landscape components located on the vertical plane. The fact that plants and urban furniture become the main focal points in heatmaps proves that components creating strong forms, shadow effects, and vertical silhouettes should be prioritized in the construction of local identity, rather than horizontal planes such as pavements.
- The perception of pavements as a "passive background" offers designers the opportunity to use these areas as a "base" that will highlight plant forms and equipment elements. A correct proportion-balance balance to be established between the vertical forms of plants and the horizontal plane of the pavement will increase the visual comfort of users. In this direction, the ground should be transformed into a visually more active component through material changes, color contrasts, or original pattern studies. Thus, in Konya's landscape identity, the ground will cease to be a transition area and become a qualified design element that increases the perceptual richness of the space.
- The dominance of plants in visual perception should be designed in a balance with hard ground and equipment elements. Considering that pavements have the lowest visual interest; wide and static pavement areas should be fragmented with plant textures, thus breaking visual monotony with a setup that goes from the part to the whole in the design. This approach will provide continuity in spatial perception by reducing the passive effect of the ground and will bring the user's visual discovery process within the park to a more dynamic structure.

Scientific Ethics Declaration

* The author declares that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the author.

* The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Scientific Ethics Evaluation Board of the Faculty of Architecture and Design, Selçuk University (Decision No: 05/01, approved on 13 November 2024).

Conflict of Interest

* The author declares that there is no conflict of interest

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Author(s) Information

Ruhugul Ozge Gemici

Selcuk University, Faculty of Architecture and Design,
Department of Landscape Architecture Selçuklu, Konya,
Türkiye
ORCID iD: <https://orcid.org/0000-0001-7477-0268>*
Contact e-mail: ozgeocak@selcuk.edu.tr

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Influence of Alloying Elements on the Kinetics of Austenite Transformation in Powder Steels

Maxim Egorov

Don State Technical University

Rimma Egorova

Don State Technical University

Michail Chaava

Don State Technical University

Filipp Pastuhov

Don State Technical University

Abstract: Structural materials obtained by powder metallurgy methods are the most common type of such products, widely used in mechanical engineering and instrument making. This paper investigates the features of the formation of the structure and properties of alloyed powder steels. The study analyzes the influence of the method of introducing alloying components (carbide-forming elements Cr, Mo, W), their dispersity, as well as sintering parameters on the homogenization of the material. It is shown that complete dissolution of alloying elements, especially large particles, requires high temperatures (up to 1300°C) and long isothermal holdings. Particular attention is paid to the effect of porosity on the kinetics of austenite transformation. It has been established that an increase in porosity reduces the incubation period and increases the temperature of the onset of the martensitic transformation (Mn point). The influence of chromium and molybdenum on the critical points Ac_1 and Ac_3 , as well as on the hardness after quenching, is analyzed. It is shown that in complex-alloyed powder steels, due to chemical heterogeneity, insoluble carbides may form, reducing the hardness of the material.

Keywords: Powder metallurgy, Alloying elements, Sintering, Porosity, Austenite transformation

Introduction

Powder Metallurgy (PM) encompasses the production of metal powders, as well as articles made from them or their mixtures with non-metallic powders. A distinguishing feature of PM from other methods is that within a single technological process, both the formation of the powder material (charge) and the shaping of the finished product from this material occur, followed by subsequent processing. Powder metallurgy, at first glance, represents a symbiosis of multidirectional processes in which a monolithic material is first dispersed into a powder, and then this powder is reconsolidated into a solid body. However, this technology remains viable due to its advantages compared to other methods. In, the author presents the following advantages of powder metallurgy and its benefits over other technological processes, which make it attractive and cost-effective for manufacturing various materials and products with unique properties and high precision.

Powder metallurgy has a number of disadvantages and limitations, such as increased costs for materials and equipment, the need for specific operations and requirements, and the fact that it is only justified in large-scale production. These disadvantages and limitations should be considered when choosing this technology for a

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specific production application. (Agureev et al.,2020, Baek, et al.,2020, Dorofeyev 2019). Despite certain drawbacks, powder metallurgy technology is actively used in industries requiring large-series or mass production of articles, as its advantages outweigh the disadvantages under these conditions. Authors in works note the significant development of powder metallurgy in the field of creating special steels and alloys (heat-resistant, tool steels, those possessing high strength and superplasticity). A great contribution to the development of powder metallurgy was made by such outstanding scientists as: Balshin, Kiparisov, Antsiferov, Fedorchenko, Andrievsky, Skorokhod, Kovalchenko, and Dorofeev. In their works, they address issues of the theory of sintering powder alloys, the theory of pressing, problems of powder materials science, the theoretical foundations of hot working of porous materials by pressure, dynamic hot pressing of powder products, and much more (Egorov et al.,2024, Eremeeva et al.,2016, Soffritti et al.,2020, Stern et al.,2016). Of course, the noted features are not isolated; they are closely related and intertwined, reflecting to a certain extent the general characteristics of the development of science and technology. They are also guided by the well-known advantages of PM, namely, obtaining products with a high material utilization rate, minimizing machining, as well as the possibility of automating the production of these products and obtaining articles with unique properties.

Heat treatment is understood as a set of operations involving heating, holding at high temperatures, and cooling with the aim of changing the structure and workability of the material, improving the combination of its mechanical and physical properties without altering the shape and dimensions of the products. Heat treatment is an effective method for enhancing the physical-mechanical properties and wear resistance of steel. The specific features of sintered steels (porosity, structural heterogeneity, high oxidizability, etc.) make it difficult to use the heat treatment processing regimes developed for cast steels, although the basic regularities of the processes occurring during heating and cooling of compact steel can be transferred to sintered materials as well. Heat treatment of powder steels has a number of features, primarily due to residual porosity, as well as chemical and structural heterogeneity (Egorov et al.,2024, Beskopylny et al.,2020, Geroldinger 2023, Li et al.,2025).

Method

The work investigated powders of metals such as iron, chromium, copper, molybdenum, and nickel. Carbon was added to the charge in the form of GK-1 pencil graphite. For the preparation of the powder mixture, special high-efficiency equipment was used — a RT-NM05S double-cone mixer manufactured in Taiwan (Figure 1), which ensures high-quality mixing of components with energy and time savings.



Figure 1. RT-NM05S double-cone mixer

Table 1. Mixer technical specifications

Model	Power, kW	Voltage, V	Load Capacity, kg	Working Volume, L	Total Volume, L	Rotation Speed, rpm	Weight, kg	Overall Dimensions, L×W×H, mm
RT-NM05S	0,18	220	5	8	16	15-30	38	808×400×602

The sintering process was performed in the heat treatment laboratory of the Department of Materials Science and Metal Technology at DSTU using a PKZ-1.0-7 chamber electric furnace with a protective atmosphere (Russia) (Figure 2, Table 2). The sintering was conducted within a temperature range of 900–1150°C in a dissociated ammonia protective gas atmosphere, with sintering times varying from 15 to 180 minutes. The influence of alloying elements on the transformation of austenite must be associated with the work expended on the rearrangement of the crystal lattice.

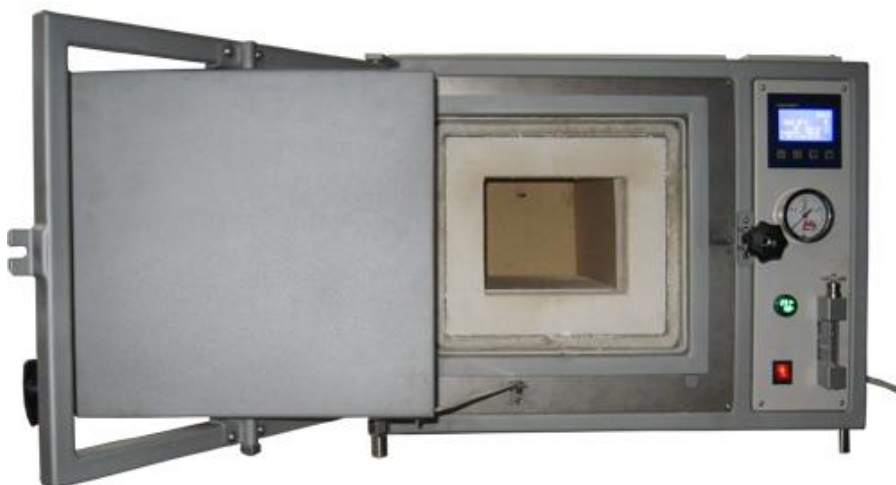


Figure 2. PKZ-1.0-7 laboratory chamber electric furnace with protective atmosphere

Table 2. Electric furnace technical specifications

Type	Tmax, °C	Gas flow rate, L/min	Working space W×H×D, mm	Overall dimensions W×H×D, mm	Power/Voltage, kW/V
PKZ -1,0-7	1300	4,1	150×180×290	795×585×605	2,5/220

The effect of nickel on the transformation kinetics of austenite in powder steels is similar to its effect in cast steels. By altering the mobility of iron atoms and the diffusion rate of carbon in α - and γ -Fe, nickel increases the stability of austenite, shifting the isothermal austenite decomposition curves downward and to the right. In high-carbon steel, the effect of nickel on the position of the isothermal decomposition curves is less pronounced than in low- and medium-carbon steel. Nickel increases the ability of austenite to undercool. Under the influence of nickel, the temperature at which the martensitic transformation begins (the Mn point) decreases; therefore, the transition of austenite to martensite occurs at a lower temperature. It increases the hardness of the austenite decomposition products, and by lowering the Mn point, it increases the amount of retained austenite (Romero-Resendiz et al.,2025, Buathong et al.,2025, Gabriel et al.,2025, Xu et al.,2025).

Copper, like nickel, increases the stability of austenite, but to a lesser extent than nickel. With an increase in porosity and a decrease in the carbon content in copper-containing steels, the duration of the incubation period decreases, the temperatures of minimum austenite stability and the start of the martensitic transformation increase, and the transformation time of austenite and the hardness of the transformation products decrease.

Results and Discussion

The most significant influence on the kinetics of austenite transformation is exerted by carbide-forming elements (Cr, Mo, W, etc.). In their presence, the duration of the incubation period and the time for complete

decomposition of austenite increase. With an increase in porosity, the total transformation time of austenite decreases, and the transformation diagram shifts to the region of higher temperatures. Thus, chromium, by increasing the stability of austenite, enhances its tendency to undercooling, significantly lowers the critical quenching rate, and improves the hardenability of steel.

Table 3. Ac_1 and Ac_3 point values of powder steels

№	Steel grade	Critical point values, °C	
		Ac ₁	Ac ₃
1	Fe+1%C	715	755
2	Fe+1%C+2%Cr	752	786
3	Fe+1%C+2%Cu	730	762
4	Fe+1%C+2%Cr+2%Cu	760	795
5	Fe+1%C+5%Cr+5%Cu	787	880
6	Fe+1%C+5%Cr+10% Mo	800	880
7	Fe+1%C+12%Cr+2% Mo	807	883

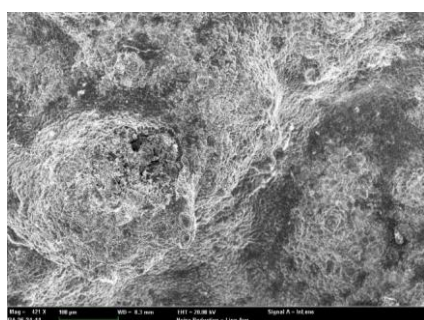
While in cast steels the position of the martensitic point is independent of the molybdenum content, in powder steels molybdenum reduces the critical cooling rate, even more significantly than chromium. Molybdenum steels exhibit high hardenability and have little tendency to overheat. The values of the critical points Ac_1 and Ac_3 for chromium-molybdenum powder steels are given in Table 3.

From the data presented in Table 3, it follows that as the chromium and molybdenum content increases, the critical points shift to the region of higher temperatures, i.e., chromium and molybdenum raise the critical points Ac_1 and Ac_3 . The hardness of these steels after quenching in water from a temperature of $Ac_1 + (30-150)^\circ C$ is given in Table 4.

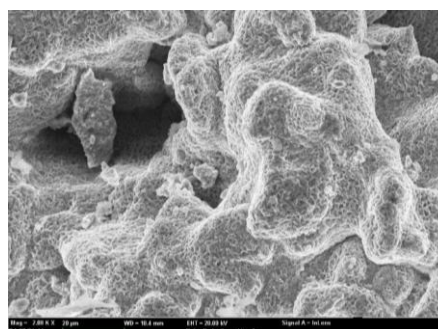
Table 4. Hardness of powder steels after quenching

№	Steel grade	Optimal quenching temperature, °C	Optimal holding time during heating for quenching, min	Hardness, HRC
1	Fe+1%C	840	10-15	56-60
2	Fe+1%C+2%Cr	860	15-20	55-58
3	Fe+1%C+2%Cu	860	15-20	52-55
4	Fe+1%C+2%Cr+2%Cu	860	20-25	48-52
5	Fe+1%C+5%Cr+5%Cu	910	20-25	41-45
6	Fe+1%C+5%Cr+10% Mo	920	25-30	38-45
7	Fe+1%C+12%Cr+2% Mo	970	25-30	34-40

From Table 4, it follows that as the content of alloying elements increases, the optimal quenching temperature rises, as does the holding time. It can also be observed that the hardness of the quenched samples decreases with an increase in the content of alloying elements. This is explained by the following. During the sintering of chromium-molybdenum steels, numerous primary, difficult-to-dissolve special carbides are formed, which do not have enough time to dissolve during heating for quenching. Since the carbide phase binds part of the carbon, its amount in the solid solution decreases, leading to the formation of low-carbon martensite and troostite, which reduce the hardness of the steel. Additionally, the inhomogeneity of the solid solution lowers the stability of supercooled austenite and shifts the Mn point to a region of higher temperatures (Kim et al.,2023, Hojati et al.,2022, Egorova et al.,2018).



a)



b)

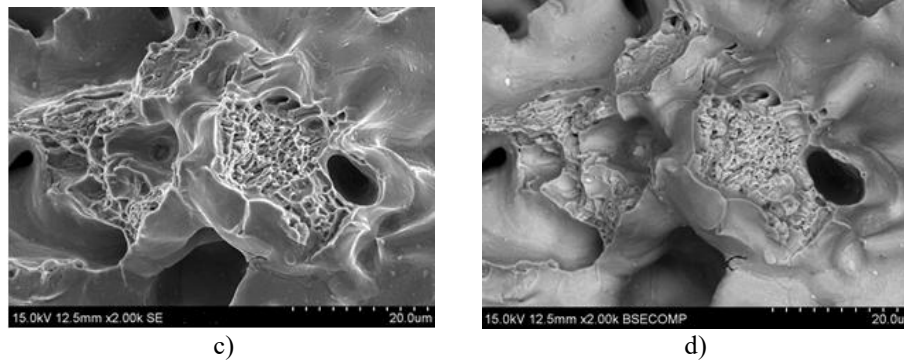


Figure 3. Fractographs of the fracture surface of Fe+1%C+12%Cr+2%Mo alloy samples fabricated under the following conditions: quenching temperature 970 °C, density 7.4 g/cm³: (a, c) carbon content 0.5%; (b, d) carbon content 0.8%

Fractographic studies of the samples quenched at 970°C showed that the fractures are characterized by a ductile-brittle fracture mechanism, which occurs along grain boundaries with ductile tear areas. The pores have a rounded shape, with a size of 5–10 µm. The ductile fracture surface indicates significant plastic deformation during failure.

For complex-alloyed steels with varying porosity, the thermokinetic diagrams are close to the austenite transformation diagrams of corresponding cast steels and are independent of porosity. The influence of porosity on the transformation kinetics is similar to its effect on the austenite transformation in carbon and singly-alloyed powder steels: an increase in porosity reduces the incubation period, increases the decomposition rate, and raises the temperature of minimum austenite stability and the temperature of the start of the martensitic transformation – the Mn point.

At the same time, the influence of porosity on the stability of austenite in complex-alloyed steels is more pronounced than in carbon steels. Thus, increasing porosity from 5% to 15% in carbon steels with 0.8% C reduces the period of minimum austenite stability by 0.3 s, while in steel 80%Fe+2%Ni+2%Cu+0.8%C, it decreases by 1.5 s.

The sintering temperature also has a significant effect on the stability of austenite in complex-alloyed steels: for example, it has been shown that increasing the sintering temperature from 1180°C to 1280°C enhances the homogeneity of austenite, increases the incubation period, widens the temperature range of maximum stability, and increases the amount of decomposed austenite.

Conclusion

In alloyed steel, complete decomposition of austenite does not occur. Retained austenite is always observed in the decomposition products. With an increase in porosity in complex-alloyed steel, the amount of retained austenite decreases. An increase in the Mn temperature leads to self-tempering of alloyed martensite, a reduction in its tetragonality, and a decrease in hardness. Significant chemical heterogeneity of steels made from complex-alloyed powder mixtures leads to the formation of carbides of the Me₃C₂, Me₇C₃, Me₂₃C₆ type that are insoluble up to the melting point. This sharply reduces (in comparison with cast steels) the incubation period and increases the critical quenching rate. As a result, even at high cooling rates in complex-alloyed steels, areas of troostite may appear alongside martensite. The presence of insoluble carbides depletes the solid solution in terms of carbon content, thereby reducing hardness.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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Author(s) Information

Maxim Egorov

Don State Technical University, Rostov-on-Don, Russia
Gagarin Square, Rostov-on-Don, 344003, Russia
ORCID iD: <https://orcid.org/0000-0002-4289-1601>
*Contact e-mail: aquavdonsk@mail.ru

Rimma Egorova

Don State Technical University, Rostov-on-Don, Russia
Gagarin Square, Rostov-on-Don, 344003, Russia
ORCID iD: <https://orcid.org/0009-0006-5871-9079>

Michail Chaava

Don State Technical University, Rostov-on-Don, Russia
Gagarin Square, Rostov-on-Don, 344003, Russia
ORCID iD: <https://orcid.org/0000-0003-3726-4950>

Filipp Pastuhov

Don State Technical University, Rostov-on-Don, Russia
Gagarin Square, Rostov-on-Don, 344003, Russia
ORCID iD: <https://orcid.org/0000-0002-0668-5739>

*Corresponding author(s) contact email

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Comparative Analysis of Earthquake-Induced Hydrodynamic Pressures in Dam–Reservoir Systems Using CFD and Analytical Methods

Ali Yildiz

Konya Technical University

Gulnaz Donmez

Konya Technical University

Mustafa Kocer

Konya Technical University

Abstract: Hydrodynamic pressures induced by earthquake excitation constitute a critical load component in the seismic safety assessment of dam–reservoir systems. In this study, earthquake-induced dynamic pressures acting on a rigid dam face were investigated numerically and compared with classical analytical approaches. A three-dimensional reservoir model with dimensions of $3\text{ m} \times 3\text{ m} \times 4\text{ m}$ was established in ANSYS Fluent, and an initial water depth of 2.5 m was defined. The fluid domain was discretized using 5 cm cubic cells, resulting in 288000 elements. A two-phase flow model was employed, and the free-surface motion was tracked using the Volume of Fluid (VOF) method under transient conditions. As seismic input, the East–West component of the February 6 Kahramanmaraş earthquake record obtained from the Göksun station (No: 4612) was used. The strong-motion interval of the record was applied in the numerical analyses. The pressure distributions obtained from the computational fluid dynamics (CFD) model were compared with the results of the Westergaard, Von Kármán, and Zangar methods. The numerical results indicated that the location and magnitude of peak hydrodynamic pressures varied with time, whereas the classical analytical methods generally predicted the maximum pressure at the dam base. The findings show that classical methods may provide practical and conservative estimates for overall loading, while CFD analysis offers a more detailed representation of time-dependent local pressure concentrations on the dam surface.

Keywords: Hydrodynamic pressure, Dam-reservoir interaction, CFD, Seismic loading, ANSYS Fluent

Introduction

Dams are among the most critical hydraulic structures, serving essential functions in water storage, irrigation, hydroelectric power generation, flood control, and water resources management. Because of their large dimensions and the potentially severe consequences of failure, their structural safety under extreme loading conditions is of great importance. Seismic effects are particularly critical in this regard, as earthquake excitation can significantly alter the stress state of the dam body and the hydrodynamic behavior of the reservoir. During an earthquake, the relative motion between the dam and the impounded water generates additional hydrodynamic pressures on the upstream face, superimposed on the existing hydrostatic pressure. Therefore, a reliable estimation of these earthquake-induced hydrodynamic loads is essential for the seismic assessment and safe design of dam–reservoir systems (Jawad et al., 2021; Goldaran, 2022; Ye et al., 2023).

The seismic behavior of dam–reservoir systems has long been investigated using analytical methods developed under simplified physical assumptions. The pioneering work of Westergaard (1933) introduced the "added-mass" concept and provided the first rational analytical solution for hydrodynamic pressure acting on a rigid dam with a

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vertical upstream face under horizontal ground motion. Subsequently, Von Kármán (1933) examined the same problem through a momentum-based formulation, proposing a simplified alternative suitable for engineering calculations. Later, Zangar (1953) extended this framework by introducing empirical pressure coefficients for both vertical and inclined upstream faces, thereby improving the applicability of analytical calculations to practical dam geometries. More advanced studies, such as those by Housner (1957) and Chopra (1967), further refined the physical representation of the problem by considering impulsive and convective components, sloshing effects, fluid compressibility, and dam flexibility. These studies collectively form the theoretical foundation of modern dam–reservoir interaction analysis (Westergaard, 1933; Von Kármán, 1933; Zangar, 1953; Housner, 1957; Chopra, 1967). Despite their practical value, classical analytical methods rely on several simplifying assumptions, such as rigid dam behavior, incompressible and inviscid fluid motion, and idealized pressure distributions that are generally expressed only as a function of water depth. These assumptions make the methods attractive for rapid preliminary evaluation; however, they may not fully capture the transient and spatially varying nature of hydrodynamic pressures under real earthquake records. In particular, local pressure concentrations, temporal phase changes, and free-surface effects may not be adequately represented by simplified closed-form solutions. For this reason, numerical approaches have become increasingly important in recent years, especially in studies where fluid–structure interaction and time-dependent pressure evolution must be evaluated in greater detail (Goldaran, 2022; Ye et al., 2023).

In this context, Computational Fluid Dynamics (CFD) offers a robust framework for simulating transient fluid motion and evaluating hydrodynamic pressure distributions on dam surfaces under seismic excitation. Addressing this need, the present study investigates earthquake-induced hydrodynamic pressures acting on a rigid dam face using a three-dimensional CFD model developed in ANSYS Fluent. The numerical results are compared with the classical analytical approaches of Westergaard, Von Kármán, and Zangar in terms of pressure magnitude and distribution. Thus, the study aims to assess the applicability of widely used classical methods for practical engineering calculations and to demonstrate the contribution of CFD-based modeling to a more refined understanding of dam–reservoir interaction under earthquake loading.

Method

Analytical Calculation Approaches

The analytical component of this study is strategically established to serve as a rigorous benchmark for evaluating and validating the numerical results derived from the Computational Fluid Dynamics (CFD) model. In the field of dam engineering, while numerical methods offer high spatial resolution, their accuracy is inherently dependent on factors such as mesh convergence, turbulence modeling, and temporal discretization; therefore, comparing these results with established theoretical solutions is a critical step in ensuring the reliability of the CFD simulation. To this end, three classical approaches—the Westergaard (1933), Von Kármán (1933) and Zangar (1953) methods—were selected for this comparative framework due to their widespread adoption in international design codes and their reliance on deterministic, closed-form, or semi-empirical formulations. These methods remain the cornerstone of seismic dam analysis, providing a clear mathematical baseline that is free from the numerical oscillations often encountered in transient simulations. The primary objective of employing these analytical formulations is to systematically determine the hydrodynamic pressure distribution across the vertical profile of the dam, the resultant hydrodynamic force, and the precise location of the pressure center. By calculating these parameters under controlled conditions, a direct point-by-point comparison can be performed against the transient pressure data extracted from ANSYS Fluent, thereby not only validating the CFD model's predictive capability but also highlighting the specific conditions under which classical assumptions may deviate from the complex fluid behavior captured by the Navier-Stokes equations.

Common Assumptions

The analytical framework adopted in this study is predicated on several idealized physical assumptions that define the interaction between the reservoir fluid and the dam structure. In the selected approaches of Westergaard (1933), Von Kármán (1933), and Zangar (1953), the reservoir water is treated as an incompressible, inviscid, and irrotational fluid, thereby neglecting the effects of internal friction and potential energy dissipation within the fluid medium. The seismic excitation is characterized as a purely horizontal ground acceleration acting on the dam–reservoir system, with the dam body itself idealized as a perfectly rigid structure. Consequently, the analysis focuses on the hydrodynamic pressure generated by the rigid-body motion of the dam face against the impounded water, rather than the complex deformations involving dam flexibility. While the formulations of Westergaard

(1933) and Von Kármán (1933) are specifically constrained to a vertical upstream face, the Zangar (1953) method extends this applicability by incorporating empirical pressure coefficients that account for various upstream face inclinations. These fundamental simplifications allow for the derivation of depth-dependent pressure distributions, providing a consistent and common analytical basis for the comparative evaluation of the transient numerical results obtained in this study.

Notation

In the analytical formulations, ρ denotes the water density, a_g is the horizontal ground acceleration, y is the depth variable used in the analytical formulations along the upstream dam face, and h is the total water depth. In addition, $m_a(y)$ represents the equivalent added mass per unit width at depth y , $p(y)$ is the hydrodynamic pressure, S_0 is the resultant hydrodynamic force, and y_c is the location of the pressure center. In the Zangar formulation, C_h denotes the hydrodynamic pressure coefficient associated with the upstream dam-face geometry.

Westergaard Method (1933)

The Westergaard method is one of the earliest analytical approaches developed for evaluating earthquake-induced hydrodynamic pressures on rigid dams. The method is based on the added-mass concept and assumes that a portion of the reservoir water moves together with the rigid dam face during horizontal earthquake excitation. Under the assumptions of incompressible and inviscid fluid motion, rigid dam behavior, and a vertical upstream face, the hydrodynamic pressure distribution can be expressed as follows.

According to Westergaard, the depth-dependent added mass distribution is given by Equation (1).

$$m_a(y) = \frac{7}{8} \rho \sqrt{yh} \quad (1)$$

The hydrodynamic pressure is obtained by multiplying the added mass by the horizontal ground acceleration, as given in Equation (2).

$$p(y) = m_a(y) a_g \quad (2)$$

Thus, the hydrodynamic pressure distribution can be written as Equation (3).

$$p(y) = \frac{7}{8} \rho a_g \sqrt{yh} \quad (3)$$

In this approach, the pressure center is generally taken at approximately two-fifths of the water depth from the dam base.

Von Kármán Method (1933)

The Von Kármán method evaluates earthquake-induced hydrodynamic pressure by using a momentum-based analytical formulation. Similar to the Westergaard approach, the method assumes that the dam body is rigid, the reservoir fluid is incompressible and inviscid, and the excitation acts horizontally. However, the equivalent added-mass distribution is represented by a different expression, which leads to a modified pressure profile along the dam face.

According to the Von Kármán formulation, the depth-dependent added mass distribution is given by Equation (4).

$$m_a(y) = \rho \left(\frac{4}{3} \sqrt{yh} - \frac{y^2}{h} \right) \quad (4)$$

The hydrodynamic pressure is obtained from Equation (5).

$$p(y) = m_a(y) a_g \quad (5)$$

Thus, the pressure distribution becomes Equation (6).

$$p(y) = \rho a_g \left(\frac{4}{3} \sqrt{yh} - \frac{y^2}{h} \right) \quad (6)$$

The resultant hydrodynamic force acting on the dam face is expressed by Equation (7).

$$S_0 = \frac{5}{8} \rho a_g h^2 \quad (7)$$

The pressure center is taken as Equation (8).

$$y_c = \frac{2}{5} h \quad (8)$$

These expressions show that the Von Kármán approach also predicts a nonlinear hydrodynamic pressure distribution and provides a practical analytical basis for comparison with numerical results.

Zangar Method (1953)

The Zangar method is a practical analytical approach developed for estimating earthquake-induced hydrodynamic pressures on both vertical and inclined dam faces. Unlike the Westergaard and Von Kármán methods, the Zangar formulation introduces an empirical hydrodynamic coefficient to account for the effect of the upstream face geometry. Owing to its simple coefficient-based structure, the method is widely used in engineering practice for approximate evaluation of hydrodynamic pressure, resultant force, and pressure center.

According to the Zangar formulation, the hydrodynamic pressure distribution along the dam face is given by Equation (9).

$$p(y) = C_h \rho g h \left(1 - \frac{y}{h} \right)^{1.5} \quad (9)$$

For a vertical upstream face, the hydrodynamic coefficient is expressed by Equation (10).

$$C_h = 0.726 \frac{a_g}{g} \quad (10)$$

For an inclined upstream face, the modified hydrodynamic coefficient is given by Equation (11).

$$C_{h,\alpha} = C_h (1 - 0.01\alpha) \quad (11)$$

The resultant hydrodynamic force acting on the dam face can be approximated by Equation (12).

$$S_0 \approx 0.54 \rho a_g h^2 \quad (12)$$

The pressure center is taken as Equation (13).

$$y_c \approx 0.4h \quad (13)$$

These equations indicate that the Zangar method provides a simplified yet practical means of representing earthquake-induced hydrodynamic pressure, particularly when the influence of face inclination needs to be included in the analysis.

Numerical Model

Geometry and Mesh

To evaluate the transient hydrodynamic loads exerted on the dam face during seismic excitation, a three-dimensional numerical simulation was performed using the pressure-based solver in ANSYS Fluent. The computational domain was designed to represent a discretized reservoir volume with dimensions of 3 m×3 m×4 m (L×W×H). To define the fluid-structure interface and the reservoir boundaries, all peripheral surfaces of the domain were characterized as rigid wall boundary conditions. The spatial discretization of the fluid domain was achieved using a structured meshing approach consisting of high-quality hexahedral (cubic) meshes. Each mesh was defined with a uniform edge length of 50 mm (5 cm), ensuring a consistent mesh topology throughout the reservoir. Consequently, the final numerical model comprised a total of 288,000. This specific mesh density was selected after a preliminary sensitivity analysis to provide sufficient spatial resolution for capturing localized pressure gradients while maintaining computational efficiency and manageable processing times. The detailed geometry of the reservoir domain and the corresponding structured mesh configuration utilized in the transient analyses are illustrated in Figure 1.

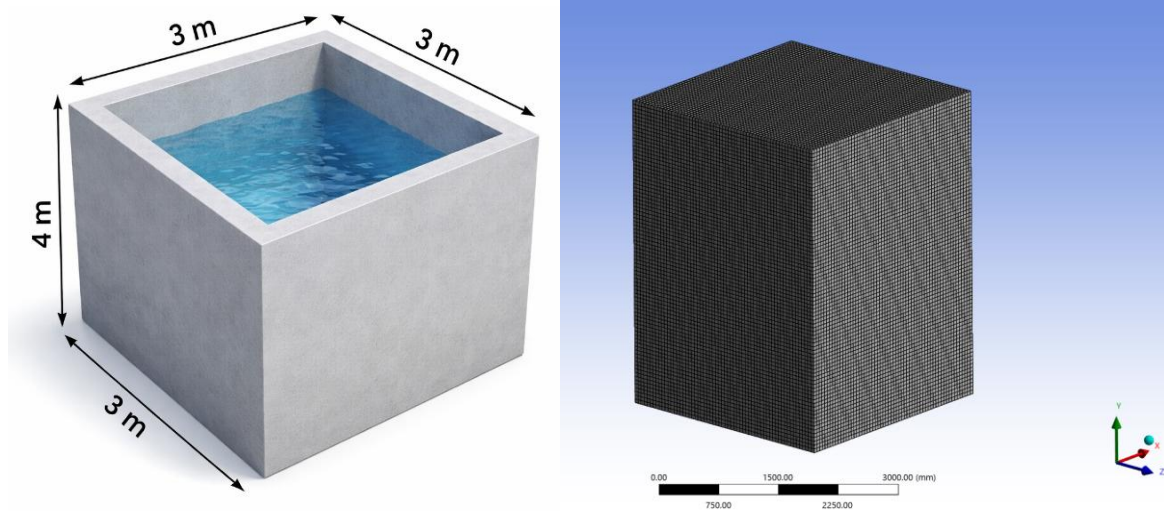


Figure 1. Geometry of the reservoir domain and structured mesh used in the numerical model.

Multiphase Flow Setup

Since the seismic response of the reservoir involves free-surface motion, water and air were defined together by using a two-phase flow model. The transient movement of the free surface was tracked by the Volume of Fluid (VOF) method. At the beginning of the analysis, the initial water level in the reservoir was taken as 2.5 m, and the remaining upper region was assigned as air. In order to ensure numerical stability and to capture the time-dependent fluid motion with sufficient accuracy, small time increments in the range of 0.01–0.005 s were used throughout the transient analyses. The initial water level and the two-phase water–air configuration adopted in the numerical model are shown in Figure 2.

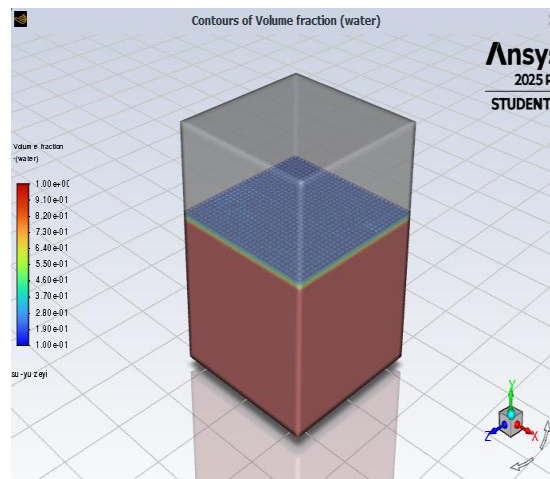


Figure 2. Initial water level and two-phase water–air setup used in the VOF-based numerical model.

Seismic Input

The seismic excitation utilized in the numerical simulations was derived from the East–West (E-W) acceleration-time history recorded at the Kahramanmaraş/Göksun station (Station No: 4612) during the catastrophic earthquake of February 6, 2023. Within the computational framework, gravitational acceleration was consistently applied in the negative Y-direction as $g=9.81 \text{ m/s}^2$. The real-world earthquake-induced acceleration record was prescribed in the positive X and Z directions to evaluate the multidimensional hydrodynamic response of the reservoir. To optimize computational resources while capturing the most significant seismic effects, the analysis focused on the "strong-motion" interval of the record. Specifically, the 20-second window between $t=25 \text{ s}$ and $t=45 \text{ s}$, representing the peak seismic energy release and the highest acceleration amplitudes, was extracted for the transient simulations. The complete acceleration-time history and the delineated strong-motion interval employed in this study are illustrated in Figure 3.

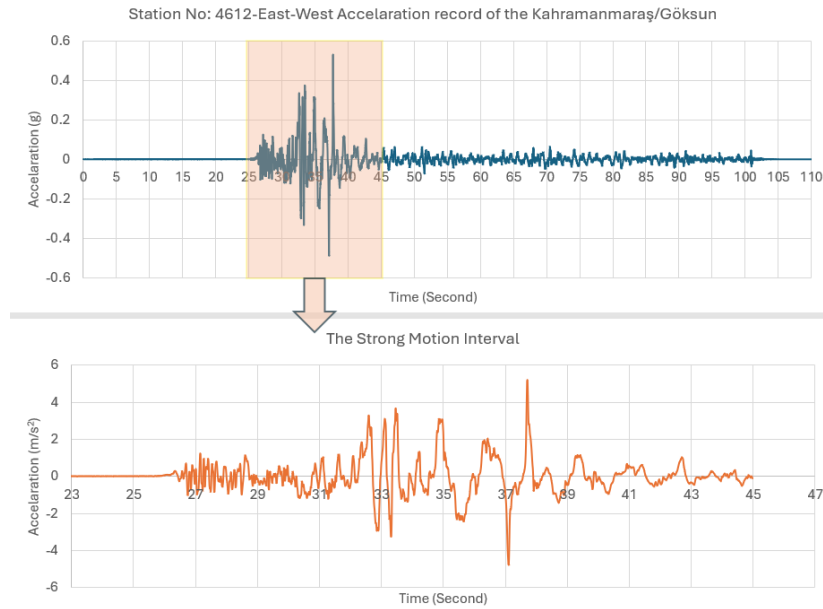


Figure 3. East–West acceleration record of the Kahramanmaraş/Göksun station and the strong-motion interval used in the numerical analyses.

Evaluation Procedure

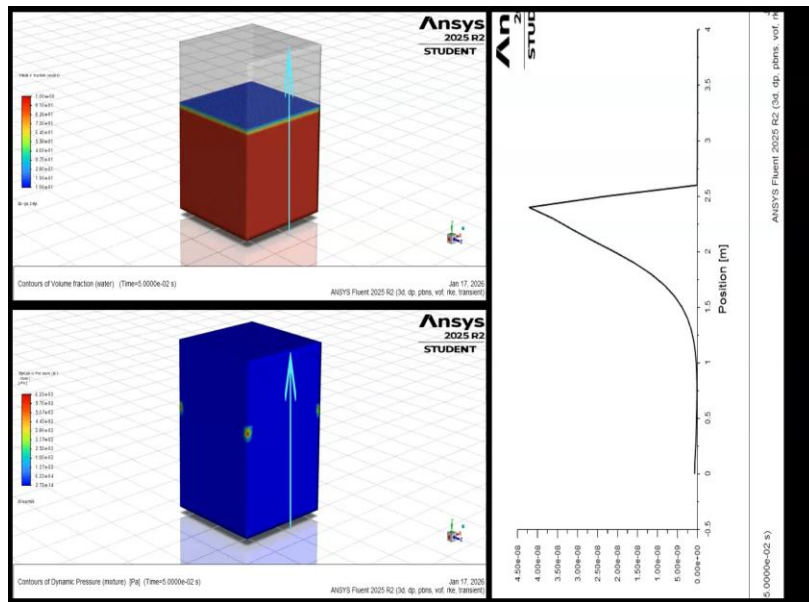


Figure 4. Free-surface response, dynamic pressure contour, and pressure profile extracted along the selected vertical line on the dam wall.

The purpose of the numerical analysis was to determine the time- and depth-dependent hydrodynamic pressure distributions acting on the dam face during earthquake excitation. In addition to the transient free-surface response, the variation of dynamic pressure along the dam wall was monitored throughout the analysis. Pressure values were extracted along a vertical line located on the wall in the Z direction, and the resulting distributions were used for comparison with the analytical methods. According to the obtained results, the highest dynamic pressure values were observed at $t = 15.3$ s and $t = 15.6$ s. Therefore, these critical time steps were selected for comparison with the Westergaard, Von Kármán, and Zangar approaches. The free-surface response, dynamic pressure contour, and the extracted pressure profile along the selected vertical line are illustrated in Figure 4.

Results and Discussion

Pressure Distribution at Critical Times

The transient numerical simulations reveal that the hydrodynamic pressure exerted on the dam face undergoes significant temporal and spatial variations throughout the seismic excitation. Based on the ANSYS Fluent results, the most critical hydrodynamic responses—characterized by peak pressure magnitudes and gradients—were identified at $t=30.55$ s and $t=31.85$ s. Consequently, these two specific time instants were selected as the primary focal points for a detailed comparative analysis with the classical analytical approaches. As illustrated in Figure 5, the dynamic pressure distributions derived from the CFD model exhibit a clear time-dependent nature that contrasts with the static profiles of analytical solutions. The numerical curve at $t=30.55$ s demonstrates a distinct localized peak, whereas the response at $t=31.85$ s reflects a lower pressure intensity across the majority of the depth range. This discrepancy highlights that the reservoir's hydrodynamic behavior cannot be simplified into a single static pattern; rather, it is intrinsically linked to the instantaneous fluid kinematics, transient oscillations, and free-surface fluctuations captured by the Navier-Stokes equations.

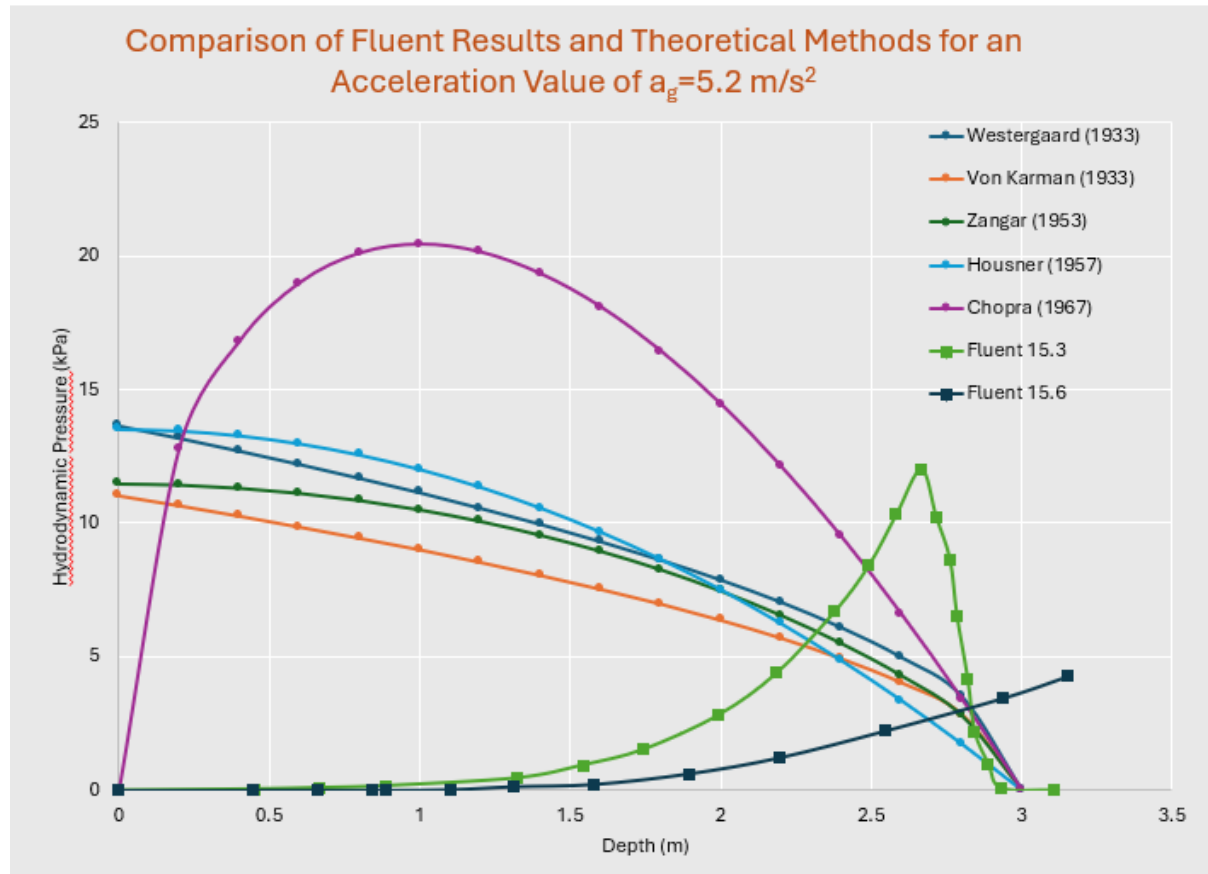


Figure 5. Comparison of dynamic pressure distributions obtained from Theoretical Methods and ANSYS Fluent for $a_g = 5.2 \text{ m/s}^2$.

Comparison of Analytical and CFD Results

The Westergaard, Von Kármán, and Zangar approaches were compared with the numerical results obtained from ANSYS Fluent in order to evaluate their capability in representing earthquake-induced dynamic pressure on the rigid dam face. In general, all three analytical methods predict smooth depth-dependent pressure distributions derived from simplified assumptions such as rigid dam behavior and idealized fluid response. By contrast, the CFD model captures the transient free-surface motion and the time-dependent development of local pressure concentrations. As summarized in Table 2, the approximate peak dynamic pressure obtained from the Fluent model at $t = 15.3$ s is about 11.9–12.0 kPa, while the secondary critical response at $t = 15.6$ s is about 4.2–4.3 kPa. Among the three analytical methods, Westergaard gives the highest peak value, approximately 13.5–13.6 kPa, whereas Von Kármán and Zangar yield lower peak values of approximately 10.7–10.9 kPa and 11.1–11.3 kPa, respectively. In terms of peak-pressure magnitude, the Von Kármán and Zangar curves are closer to the primary Fluent response than the Westergaard curve. However, the numerical results also show that the location of the peak dynamic pressure changes with time, whereas the analytical methods assume predefined idealized pressure profiles. Therefore, the analytical methods can reproduce the general magnitude level of the dynamic response, but they do not fully capture its transient localization.

Table 2. Approximate peak dynamic pressures read from Figure 5

Method	Approximate peak dynamic pressure (kPa)	Approximate coordinate of peak on plotted axis (m)	General observation
Westergaard (1933)	13.5–13.6	0.0	Smooth, relatively conservative
Von Kármán (1933)	10.7–10.9	0.0	Close to main Fluent peak
Zangar (1953)	11.1–11.3	0.0	Close to main Fluent peak
Fluent 15.3	11.9–12.0	2.65–2.70	Primary critical transient peak
Fluent 15.6	4.2–4.3	3.10–3.15	Secondary critical response

A comparison based on Table 2 indicates that the three analytical methods follow the same general trend as the CFD model in terms of dynamic-pressure level, but the numerical model provides a more realistic description of the spatially localized and time-dependent pressure evolution.

Hydrostatic and Hydrodynamic Force Assessment

To improve the engineering interpretation of the results, the dynamic pressure distributions should be evaluated together with the hydrostatic loading already acting on the dam face. For a vertical wall retaining water, the hydrostatic pressure increases linearly with depth and represents the basic static loading component prior to earthquake excitation. Accordingly, the earthquake-induced hydrodynamic pressure should be interpreted as an additional transient increment superimposed on the pre-existing hydrostatic pressure field.

For the adopted reservoir condition, the initial water depth was taken as $h = 2.5$ m. Based on this water depth, the hydrostatic pressure at the base, the resultant hydrostatic force per unit width, the overturning moment about the base, and the hydrostatic pressure center were calculated analytically. These reference values are given in Table 3.

Table 3. Hydrostatic reference values for $h = 2.5$ m

Quantity	Expression	Value
Base hydrostatic pressure	$p_{h(y)} = \rho g y$	24.53 kPa
Resultant hydrostatic force per unit width	$S_h = \frac{1}{2} \rho g h^2$	30.66 kN/m
Overturning moment about base	$M_h = \frac{1}{6} \rho g h^3$	25.55 kN·m/m
Pressure center below free surface	$y_{c,h} = \frac{2h}{3}$	1.67 m
Pressure center above base	$y_{c,h} = \frac{h}{3}$	0.83 m

As seen in Table 3, the hydrostatic component is already significant before the dynamic increment is considered. When the maximum CFD-based dynamic pressure of about 12.0 kPa is compared with the base hydrostatic pressure of 24.53 kPa, it is clear that the hydrodynamic effect acts as a substantial transient addition rather than

as the dominant component. In other words, the dynamic peak corresponds to nearly half of the hydrostatic base pressure and should therefore be included in the assessment together with the hydrostatic load. To visually support this interpretation, a simple hydrostatic pressure diagram may be added as Figure 6.

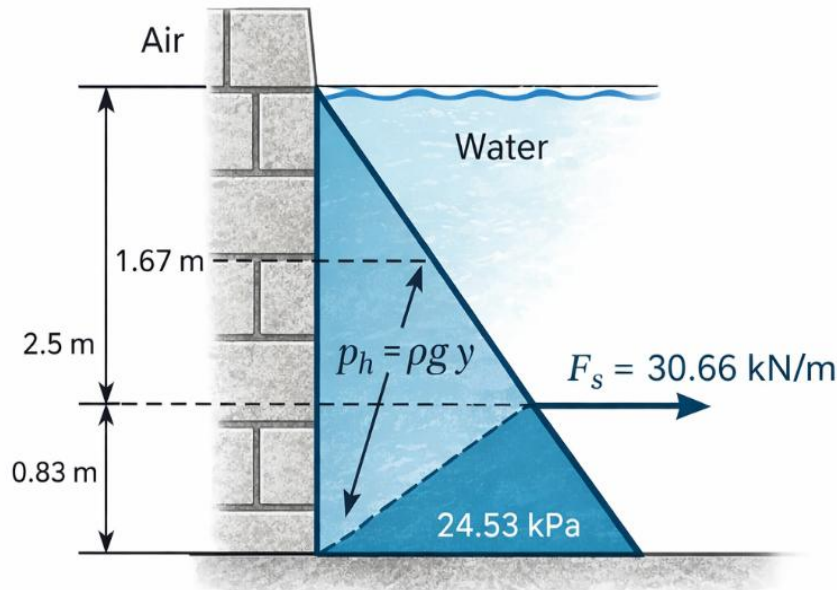


Figure 6. Idealized hydrostatic pressure distribution and resultant hydrostatic force acting on the dam face.

Engineering Interpretation

From an engineering point of view, the analytical methods remain useful for rapid and practical estimation of dynamic pressure levels. Their main advantage lies in their simplicity and ease of implementation. However, the present comparison shows that these methods provide idealized pressure distributions and do not fully represent the strongly localized character captured by the CFD model. In particular, the Fluent result at $t = 15.3$ shows a narrow and pronounced local peak, whereas the analytical curves remain smoother and more distributed along the plotted depth coordinate. This suggests that the analytical approaches are more appropriate for preliminary or conservative estimation of the dynamic component, while CFD-based analysis is more suitable for identifying local and time-dependent pressure concentrations on the dam face. Another important outcome is that the hydrostatic load is not negligible when compared with the earthquake-induced dynamic increment. As shown in Table 3, the base hydrostatic pressure for the adopted water depth is 24.53 kPa, whereas the main CFD-based dynamic peak is approximately 12.0 kPa. Therefore, the pressure demand on the dam face should not be interpreted only through the dynamic increment; instead, hydrostatic and hydrodynamic effects should be considered together. Accordingly, the Westergaard, Von Kármán, and Zangar methods may be considered suitable for preliminary and practical estimation of the dynamic component, whereas CFD-based modeling provides a more realistic basis for evaluating transient pressure localization and time-dependent wall-pressure evolution.

Conclusion

The main conclusions of this study can be summarized as follows:

1. The ANSYS Fluent analyses showed that the dynamic pressure distribution on the dam face is strongly time-dependent under earthquake excitation, and the most critical responses were observed at $t = 15.3$ and $t = 15.6$ s.
2. The primary CFD-based dynamic peak was approximately **11.9–12.0 kPa** at $t = 15.3$ s, while the secondary critical response at $t = 15.6$ was approximately **4.2–4.3 kPa**.
3. Among the three analytical methods considered in the study, the **Von Kármán** and **Zangar** approaches showed closer agreement with the primary Fluent peak than the **Westergaard** approach in terms of peak dynamic-pressure magnitude.
4. The analytical methods provide smooth and idealized pressure distributions, whereas the CFD model reveals localized and transient pressure concentrations that vary during the excitation. Therefore, analytical

formulations are useful for preliminary assessment, but they do not fully represent the time-dependent character of the hydrodynamic response.

5. For the adopted water depth of **2.5 m**, the hydrostatic base pressure was calculated as **24.53 kPa**, and the resultant hydrostatic force per unit width was **30.66 kN/m**. This indicates that the hydrodynamic effect acts as a significant transient increment superimposed on an already substantial hydrostatic load.
6. The results confirm that a realistic seismic assessment of the dam face should consider the combined action of hydrostatic and hydrodynamic pressures rather than evaluating the dynamic component alone.

Recommendations

Future studies should focus on obtaining direct CFD-based force and pressure-center data from exported numerical results. In addition, dam flexibility, different reservoir levels, and multiple earthquake records should be considered in order to improve the physical realism of the analysis. The applicability of the analytical methods may also be further examined for inclined dam faces and different geometric configurations. Finally, hydrostatic and hydrodynamic effects should be assessed together for a more realistic evaluation of the total pressure demand acting on dam surfaces.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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Author(s) Information

Ali Yıldız

Konya Technical University, Faculty of Engineering and
Natural Sciences, Department of Civil Engineering
Konya, Türkiye
ORCID iD: <https://orcid.org/0000-0002-6909-6114>
*Contact e-mail: ayildiz@ktun.edu.tr

Mustafa Kocer

Konya Technical University, Faculty of Engineering and
Natural Sciences, Department of Civil Engineering
Konya, Türkiye
ORCID iD: <https://orcid.org/0000-0002-5505-2065>

Gulnaz Donmez

Konya Technical University, Faculty of Engineering and
Natural Sciences, Department of Civil Engineering
Konya, Türkiye
ORCID iD: <https://orcid.org/0009-0001-8191-3623>

*Corresponding author(s) contact email

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Study of the Process of Hydrogen Accumulation in Nickel-Cadmium Batteries Taking into Account the Service Life

Nataliya Yazvinskaya

Don State Technical University

Dmitry Galushkin

Don State Technical University

Yuriy Astsaturov

Don State Technical University

Lyudmila Tomilina

Don State Technical University

Abstract: This research addresses a critical aspect of battery management and automation in energy storage systems: hydrogen accumulation in nickel-cadmium batteries during operational cycles. From an automation perspective, understanding hydrogen generation mechanisms is crucial for developing intelligent battery monitoring and control systems. The study employs advanced thermal decomposition techniques and volumetric gas analysis to quantify hydrogen accumulation in battery electrodes over time. By systematically investigating KSL-15 and KPL-14 batteries with a service life of 0 to 10 years, we found a direct proportional relationship between hydrogen volume and service life, and identified where in the electrode hydrogen accumulates. Key findings have significant implications for automated battery management technologies. The research demonstrates that hydrogen accumulates predominantly in cadmium and nickel oxide electrodes, with volumes reaching up to 290 liters in specific battery configurations. This knowledge enables the development of more sophisticated automated monitoring algorithms that can predict battery degradation and potential safety risks. The study's methodology provides a framework for integrating real-time hydrogen detection and measurement into battery management systems, potentially enhancing predictive maintenance strategies and improving overall energy storage system reliability through advanced technological process automation.

Keywords: Nickel-cadmium, Hydrogen accumulation, Service life

Introduction

Technological process automation in battery systems involves sophisticated monitoring of critical parameters such as hydrogen accumulation, charge-discharge cycles, and thermal characteristics. Understanding the intricate mechanisms of hydrogen generation and accumulation within battery electrodes is paramount for developing intelligent battery management systems. These automated systems can potentially predict battery degradation, prevent thermal runaway, and optimize charging protocols.

A significant operational challenge associated with batteries is the phenomenon of aging, which is closely linked to electrolyte degradation and gas evolution. Several factors can contribute to the occurrence of thermal runaway in batteries, including overcharging, short circuits, manufacturing defects, and physical damage to the battery. When a battery is overcharged, the voltage at the electrodes increases, leading to the production of excess heat. This can cause the electrolyte in the battery to decompose, releasing gases that can lead to further heating

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and potentially cause the battery to explode (Galushkin et al., 2015). Short circuits can also cause thermal runaway by creating a path for a large current to flow through the battery, leading to the rapid generation of heat. Manufacturing defects, such as contamination of the electrolyte or improper sealing of the battery cells, can also contribute to thermal runaway.

Once thermal runaway begins, it can be difficult to stop or control. The heat generated can lead to a chain reaction, as the increased temperature causes more heat production, leading to a rapid and uncontrolled increase in temperature. This can ultimately result in the battery exploding and potentially causing damage to the surrounding environment.

There are very few studies of this phenomenon in the literature on this topic. In our opinion, the lack of studies of thermal runaway of alkaline batteries can be explained by the following reasons. There are many hypotheses about how thermal runaway occurs in batteries, including chemical reactions inside the battery, uneven charge distribution, overheating, and other factors. However, despite the various theories, the exact mechanism of thermal runaway is still a subject of research. The authors of these scientific studies did not consider it appropriate to provide direct evidence of the mechanism under consideration based on experimental data.

The studies presented in (Abada et al., 2016; Feng et al., 2014; Kim et al., 2014; Lee et al., 2015; Popov et al., 2021; Ren et al., 2014; Rezvanizani et al., 2014) demonstrated that the uncontrolled process of thermal instability in nickel-cadmium batteries is accompanied by the active release of previously accumulated hydrogen. Experimental studies (Fleischhammer et al., 2015; Friesen et al., 2016; Grutzke et al., 2015; Kraft et al., 2015) devoted to the thermal destruction of nickel-cadmium battery electrode samples revealed that the hydrogen recorded during these experiments was in the electrodes even before the onset of the thermal destruction process. The present study is aimed at a quantitative analysis of the hydrogen content that accumulates in the electrodes of nickel-cadmium battery cells during their service life.

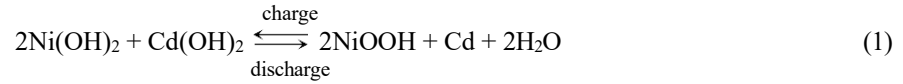
Possible sources of hydrogen formation in electrode materials of nickel-cadmium batteries are analyzed. The first possibility arises from various technological processes employed in the production of these battery electrodes. According to the second hypothesis, hydrogen accumulation can occur during battery discharges throughout the charge-discharge cycles (Li et al., 2014; Park et al., 2015). Consequently, it is hypothesized that hydrogen accumulation in the electrodes of the studied nickel-cadmium batteries is a gradual process resulting from extended battery operation. Therefore, the volume of accumulated hydrogen in the electrodes should be proportional to the battery's service life. As an example, consider a KSL-15 battery, which operates for 6 hours with a charging current of 3.8 A. This results in an overcharge of 1.52 times the battery's nominal capacity. Consequently, the overcharging of the KSL-15 battery (with a nominal capacity of 7.8 Ah) leads to the decomposition of electrolyte water, releasing hydrogen and oxygen.

The aforementioned calculation illustrates the potential for hydrogen accumulation in the electrodes of nickel-cadmium batteries with varying service life. Accordingly, it is necessary to determine the relationship between the accumulated hydrogen volume in the electrodes and the battery's operational duration. The main objective of this study is to analyze the correlation between the volume of hydrogen accumulated in the electrodes of nickel-cadmium batteries and their service life, as well as to determine the location of hydrogen accumulation using the example of KSL-15 batteries.

Materials and Methods

Experimental studies were performed on KSL-15 batteries with a service life of 0 to 7 years. In addition, KPL-14 batteries with a service life of 0 to 10 years were also used in the study. The alkaline nickel-cadmium battery consists of positive nickel oxide and negative cadmium electrodes separated by plastic separators, which ensure a stable interelectrode gap and free circulation of the electrolyte, (Figure 1).

Structurally, KSL-15 batteries are blocks of positive and negative electrodes placed in a case, where the negative terminal of the battery terminal was connected to the case, and the positive one to a terminal insulated from the case. The battery design includes metal-ceramic positive electrodes and pressed negative electrodes. A fibrous polypropylene separator provides separation. The active materials are: for the positive electrode - nickel hydroxide Ni(OH)_2 , for the negative - cadmium hydroxide Cd(OH)_2 . The electrolytic medium is represented by a solution of technical potassium hydroxide with a density of 1.22 g/cm^3 with the inclusion of technical lithium hydroxide. The fundamental reactions occurring in the battery are reflected by the equation (1):



During the process of full charging of the battery under study, hydrogen is released at the negative electrode in accordance with the reaction (2):



As the positive electrodes charge during the NiOOH formation process, oxygen is released, with its quantity increasing towards the final stage of battery charging in accordance with the reaction (3):



The oxygen that is released oxidizes the negative electrodes according to the reaction (4):



As a result, the pressure inside the accumulator does not exceed the permissible limits.

The battery KPL-14 is an electrode block consisting of positive and negative plate electrodes separated from each other by a frame plastic separator. The electrode block is placed in a rectangular tank and insulated from it by vinyl plastic gaskets. The battery cover is welded to the tank along the perimeter. Under normal operating conditions, the batteries use an electrolyte - potassium oxide hydrate with a density of 1.19 g/cm^3 with the addition of $(20 \pm 1) \text{ g/l}$ lithium oxide hydrate; at negative temperatures - potassium oxide hydrate with a density of 1.26 g/cm^3 without the addition of lithium oxide hydrate.

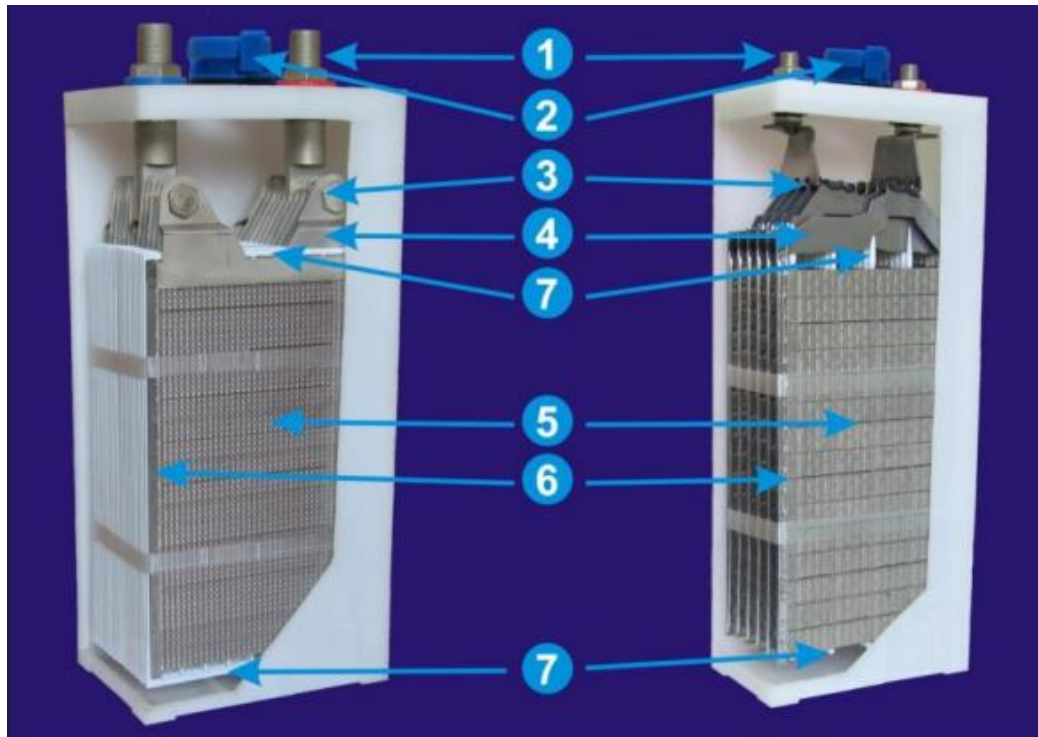


Figure 1. Construction of alkaline nickel-cadmium battery: 1. Current collector - acts as a current collector element and serves as a contact unit for the inter-battery connection; 2. Plug - is designed for convenient filling of the tank with electrolyte, unimpeded gas removal during charging and preventing electrolyte splashing and the release of aerosol particles; 3. Electrode connection - combines the electrodes into a single system and transmits electric current from the electrodes to the current terminal (conductor); 4. Contact strips - are fixed to the electrode by welding and carry out the current drain from the electrode elements; 5. Electrode; 6. Rib - gives the electrode mechanical strength and ensures conductive connection with the contact strip; 7. Separator - isolates the positive electrode from the negative and creates conditions for the free movement of electrolyte in the interelectrode space

The hermetically sealed thermal chamber for the thermal decomposition of the electrodes consists of a cylinder 1.8 m long and 2 cm in diameter. One end of the cylindrical apparatus is sealed, while a rubber stopper equipped with a gas outlet tube is inserted into the arcuate end. The sealed end is positioned within a muffle furnace. The gas generated during heating within the thermal chamber is directed into a measurement container after passing through a standardized coil. For experiments involving the thermal decomposition of battery electrodes, the electrodes are placed in a specialized cartridge, which is then inserted into the thermal chamber.

This configuration facilitates the convenient removal of the test electrode from the thermal chamber following thermal decomposition, which occurs at a temperature of 800 °C. The temperature for thermal decomposition was determined experimentally. It was established that substantial gas emission occurs from both electrode types when the temperature exceeds 740 °C. Consequently, an optimal temperature of 800 °C was selected for the experiment.

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During the experiment, each electrode underwent thermal decomposition. For this purpose, the electrode was rolled into a cylindrical shape and placed in a cartridge, which was then inserted into a thermal chamber. The thermal decomposition process was terminated when the volume of the gas mixture released per day was less than 100 milliliters, in accordance with the experimental conditions. Thermal decomposition of the nickel oxide electrode was carried out for two weeks, eleven hours a day. Thus, on the first day of the experiment, 5.5 liters of gas were extracted from the nickel oxide electrode. 3.5 liters of gas were released from the cadmium electrode during the first day. Theoretically, the following substances can be released as result of thermal runaway: water vapor, hydrogen and oxygen due to the decomposition of water and oxides in the electrodes, as well as separator combustion products. The gas accumulator was cooled and the water vapor was separated. To determine the quantitative composition of the released gas, the VOG-2M volumetric optical gas analyzer was used in the study. It is capable of determining the content of carbon dioxide, oxygen and carbon monoxide using the gas volume method, and when determining methane, the device operates by measuring the shift of the interference pattern. It consists of a burette, an absorption vessel, a pressure vessel for the sealing liquid, a pressure vessel for water, a vessel, a distribution tap, a tube «Heat Pipe», hopcalite, silica gel, a tube for activated carbon, a pressure gauge, a burette with a capacity of 275 ml. The results of the experimental studies are presented in Figures 1 and 2 for the KSL-15 and KPL-14 accumulators, respectively.

Before putting the new batteries into operation, 2 training cycles were reported for full operation of the mode: charge with a current of 0.2 C_n for 10 hours on the first cycle and 8 hours on the second cycle, discharge with a current of 0.2 C_n for 4 hours on the first cycle and to 1.0 V on the second cycle. Then a control cycle was reported with the mode: charge with a current of 0.2 C_n for 8 hours, a break of 1 hour, and discharge with a current of 0.2 C_n to 1.0 V. After that – charge with a current of 0.2 C_n for 10 hours. Upon completion of charging, the battery was disconnected from the charger. Charging was carried out from a source of direct or rectified current, the maximum working voltage of which is not less than $(2 \cdot n)$ V, where n is the number of batteries connected in series. Continuous operation in the buffer mode leads to a decrease in the capacity of the batteries. This process is reversible. To restore capacity, it is recommended, if necessary, to re-train the batteries in a mode similar to that used for commissioning. Due to thermal decomposition of the electrodes from new KSL-15 batteries at the temperature set above, about 160 ml of a mixture consisting of hydrogen and air was released. It is interesting to note the fact that when heating the thermal chamber without an electrode, approximately 130 ml of air is observed in the measuring container due to the expansion of air in the thermal chamber itself, which makes it difficult to determine the initial moment of hydrogen release from the battery electrodes and its entry into the measuring container. In this regard, during the primary thermal decomposition of the battery electrodes, 170 ml of gas is removed from the experimental setup under study, which determines the accuracy of measuring the accumulated hydrogen in the battery electrodes.

Analysis showed that the gas released was only hydrogen. The absolute error of the percentage concentration is 0.3-0.5 %. The results of the experiments are presented in (Figure 2) (KSL-15), (Figure 3) (KPL-14). The relative error of the data in Fig. 2 and 3 is 5–6 %. The next step is to determine the location of the hydrogen: whether it is concentrated in the active mass or in the metal-ceramic frame of the electrode. Experimental work was carried out using nickel oxide electrodes from KSL-15 batteries that had been in operation for six years in identical modes. Sulfuric acid with a concentration of 22.6% was used in the experiment.

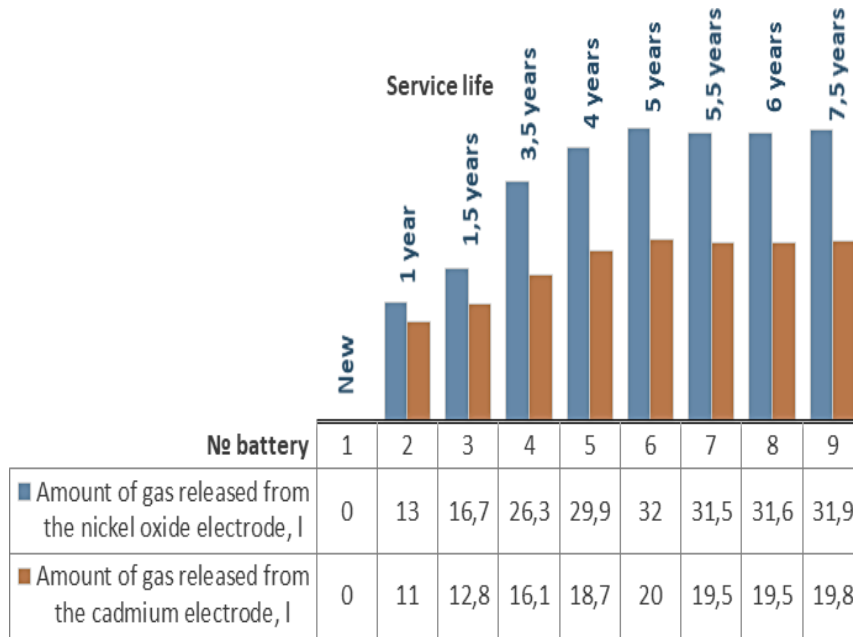


Figure 2. Mean hydrogen content in nickel oxide and cadmium electrodes of KSL-15 batteries as a function of operational duration

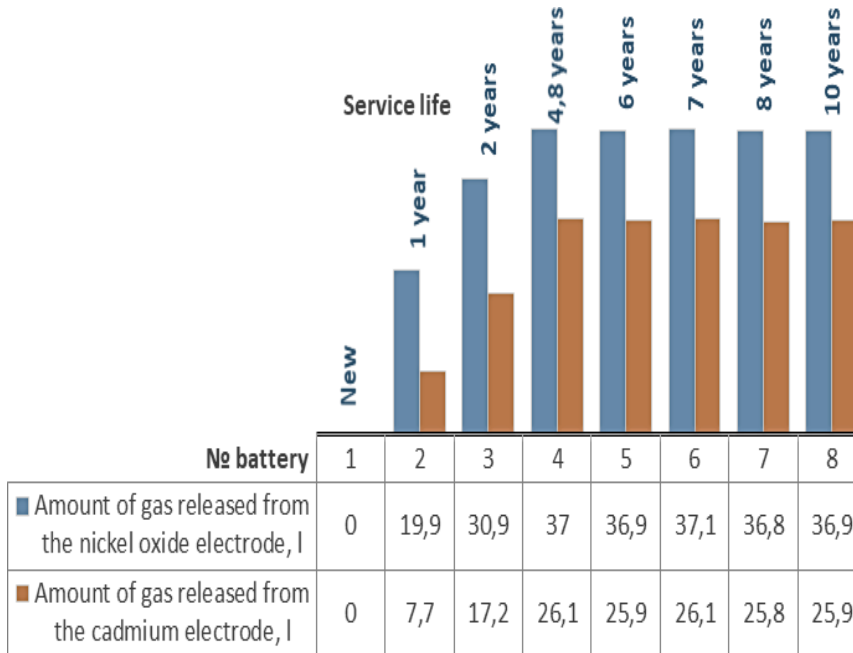


Figure 3. Mean hydrogen content in nickel oxide and cadmium electrodes of KPL-14 batteries as a function of operational duration

First of all, let us consider the probability of hydrogen accumulation in nickel hydroxide. When a nickel oxide electrode is immersed in sulfuric acid, a soluble compound NiSO_4 is formed. Based on this, when hydrogen is concentrated in nickel hydroxide either in unbound form or by forming unstable compounds with nickel hydroxide soluble in sulfuric acid, its yield will be equivalent to the amount obtained during high-temperature decomposition of the nickel oxide electrode (Figure 2 and 3). If hydrogen creates strong chemical structures

with nickel hydroxide that are not subject to destruction by sulfuric acid, then the mass of the nickel oxide electrode after acid action will be greater than the initial mass of the metal base.

Additionally, it was found that after 20-minute treatment with sulfuric acid, the mass of the nickel oxide electrode stabilized. In our studies, a treatment time of 30 minutes was used to ensure complete extraction of nickel hydroxide from the nickel oxide electrode. In addition, direct experimental data demonstrated that the sintered nickel base weakly interacts with sulfuric acid, since its mass remained unchanged after 20-minute acid treatment (the error of the scales was ± 5 mg). Hydrogen release was also not observed within the measurement accuracy of ± 5 ml.

All electrodes of the KSL-15 battery were cleaned with distilled water, dried, and their weight was determined. Then the electrodes were placed in sulfuric acid (in a sealed vessel with a gas outlet tube connected to the measuring container). After the 30-minute acid treatment, the electrodes were again washed with distilled water, dried, and weighed. The obtained data are presented in (Figure 4).

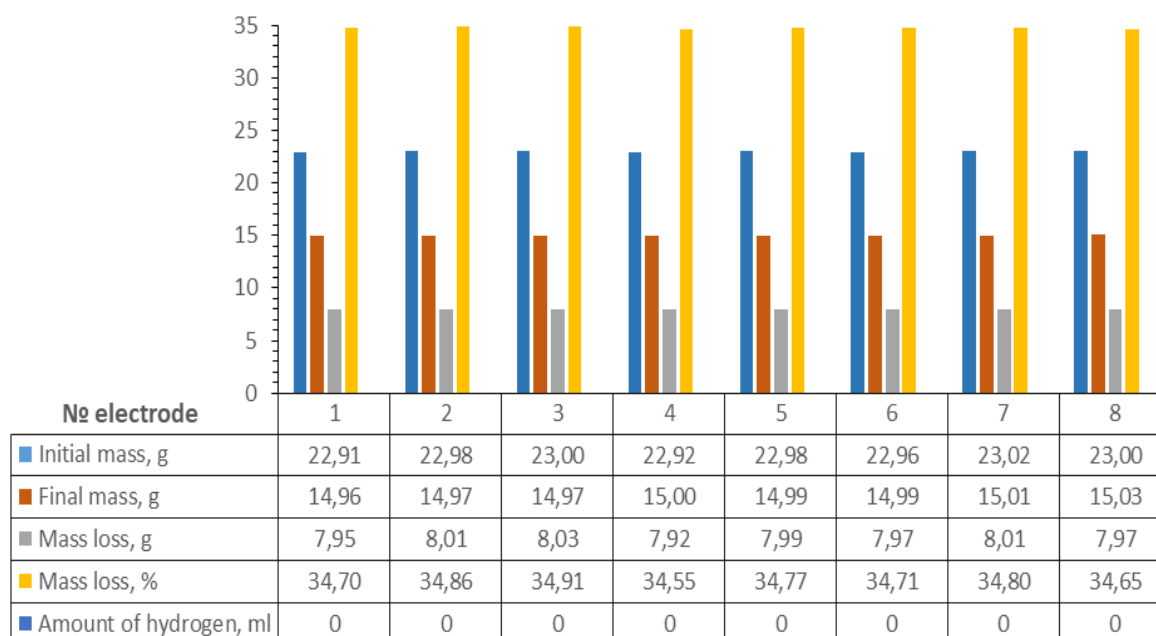


Figure 4. Etching performance in sulfuric acid of nickel oxide electrodes of KSL-15 battery

Based on the experimental results (Figure 4), the following conclusions can be formulated:

- hydrogen does not accumulate in nickel hydroxide either in free or weakly bound form, which is confirmed by the absence of gas evolution during acid etching within the measurement accuracy of ± 5 ml;
- according to the technical characteristics of the KSL-15 battery manufacturer, the content of active mass in the nickel oxide electrode is $35 \pm 1\%$.

On the experimental results (Figure 4), it can be hypothesized that hydrogen is concentrated in the metal-ceramic framework of the electrode, similar to processes in other transition metals used for hydrogen accumulation. Based on the experimental results (Figures 2 and 4), the proportion of active material in the positive electrode of a fresh nickel-cadmium battery was estimated.

The average mass of the positive electrode was 23 g (Figure 4). During the six-year operation of the KSL-15 battery, 32 l of hydrogen accumulated in its positive electrode (Figure 2), which corresponds to a mass of $32 \times 2/22.4 = 2.857$ g of hydrogen (where 22.4 l/mol is the molar volume of hydrogen, and 2 g/mol is its molar mass). Therefore, the initial mass of the positive electrode without taking into account the accumulated hydrogen was $23 - 2.857 = 20.143$ g. The mass loss of the positive electrode during treatment with sulfuric acid (which corresponds to the mass of the active material) averaged 8 g (Figure 4). Based on this, the active material content in the new positive electrode was $(8/20.143) \times 100 = 39.71\%$. According to the experimental results shown in Figure 4, the percentage of active material in the positive electrode (when converted to the original hydrogen-free electrodes) was in the range of 34.55% to 34.91%. The obtained values were consistent with the technical specifications of the KSL-15 battery manufacturer. The relative error of the experiment was 4%.

Thus, hydrogen is concentrated in the metal-ceramic frameworks of nickel oxide electrodes. As a result, during high-temperature decomposition of the metal-ceramic framework of the oxide-nickel electrode, only hydrogen is released from it, and only nickel remains. This experiment directly confirms that the metal-ceramic framework of the oxide-nickel electrode after six years of operation contains two components: hydrogen and nickel, i.e. it is a nickel hydride.

Results and Discussion

Figure 2 and 3 conclusively demonstrate that the electrodes of newly developed batteries do not contain hydrogen.

During the course of the research, a correlation was established between the volume of hydrogen accumulated in the electrode materials of nickel-cadmium batteries and their operational lifespan. It was determined that this relationship exhibits a direct proportionality. However, considering the existence of a saturation phase, it was demonstrated that the quantity of hydrogen retained in batteries after more than five years of operation remains constant. These findings are substantiated by experimental data. Furthermore, it was confirmed that the gas accumulated within the battery electrodes is predominantly hydrogen, accounting for approximately 98% of the total gas volume.

For instance, in the KSL-15 battery design, which consists of five cadmium and six nickel oxide electrodes (as illustrated in Figure 2), it can be estimated that approximately 290 liters of hydrogen will be accumulated. Similarly, for the KPL-14 battery design, comprising four cadmium and five nickel oxide electrodes (as shown in Figure 3), an accumulation of approximately 289 liters of hydrogen is anticipated. These estimated volumes of accumulated hydrogen align with previously reported values for other types of nickel-cadmium battery configurations (Feng et al., 2014; Galushkin et al., 2015; Golubkov et al., 2015; Metzger et al., 2016). The calculations presented in this example demonstrate that nickel-cadmium batteries are capable of accumulating such volumes of hydrogen over their operational lifespan.

Consequently, in order to achieve full charge, KSL-15 batteries must be recharged to 1.5 times their nominal capacity. This process results in the consumption of approximately 7.7 Ah during the charging cycle, where hydrogen and oxygen are produced through the electrolyte water decomposition reaction. Experimental observations revealed that during the charging of a KSL-15 battery, approximately 3 liters of hydrogen and 1.5 liters of oxygen are generated. This indicates that the total volume of hydrogen accumulated in KSL-15 battery electrodes, amounting to 290 liters, can be produced through thermal decomposition within approximately 97 charge-discharge cycles. Given that KSL-15 batteries typically undergo several orders of magnitude more charge-discharge cycles throughout their service life, it can be theoretically concluded that they are capable of accumulating 290 liters of hydrogen.

In the case of KPL-14 batteries (as depicted in Figure 3), which are charged with a current of 2.5 A for a duration of 10 hours, according to the technical specifications, the accumulated volume of hydrogen in their electrodes can be achieved within 68 charge-discharge cycles.

During charging, electrolytic water undergoes decomposition, accompanied by the release of hydrogen and oxygen. However, the experimental results obtained (shown in Figure 2 and 3) did not confirm the supposed accumulation of oxygen in the battery electrodes. Instead, only hydrogen was observed to accumulate. An intriguing observation was made concerning the presence of hydrogen in the electrodes of nickel oxide and cadmium batteries, particularly in significant quantities. This phenomenon is likely attributed to the high diffusion permeability of hydrogen. Specifically, the diffusion coefficient of hydrogen in nickel at a temperature of 20°C is approximately 1000 times greater than that of oxygen, as documented in references (Abe et al., 2019; Galushkin et al., 2015; Lei et al., 2017). Consequently, during the decomposition of electrolyte water into its constituent gases, hydrogen diffuses into and accumulates within the electrodes, while oxygen is more likely to escape into the atmosphere. In this case, to study the accumulation of hydrogen, oxide-nickel electrodes of KSL-15 batteries with a six-year period of operation in identical modes were used.

The active mass was extracted from the electrodes by acid etching. Then the nickel frames were subjected to high-temperature decomposition. The volume of released hydrogen corresponded to the data in Figure 4 with a relative experimental error of 3 %.

Conclusion

It is established that hydrogen gas is produced at the cadmium electrodes during the charging process of nickel-cadmium batteries. Experimental data, as illustrated in Figures 2 and 3, indicates that hydrogen accumulates on both the cadmium and nickel oxide electrodes. This phenomenon is likely due to the dense packing of sintered electrodes in KSL-15 batteries and KPL-14, allowing hydrogen generated at the cadmium electrodes to permeate into the nickel oxide electrodes and subsequently accumulate within them.

At the same time, the obtained results require in-depth experiments and theoretical justification. The research work revealed that the concentration of hydrogen in the electrode system of nickel-cadmium power elements increases during their long-term operation. The laboratory tests of hydrogen accumulation helped to clarify the process and areas of hydrogen concentration in the oxide-nickel electrodes of batteries after their long-term operation. The main results of this study:

1. The location of hydrogen accumulation was determined. It was experimentally proven that hydrogen does not accumulate in the active mass of the electrode (nickel hydroxide) either in a free or weakly bound state. This is evidenced by the absence of gas evolution during acid etching of the electrodes with sulfuric acid within the measurement accuracy of ± 5 ml.
2. Hydrogen localization in the metal-ceramic frame was established. Hydrogen is concentrated exclusively in the metal-ceramic base of the electrode, forming nickel hydride. This is confirmed by the results of high-temperature decomposition of frames cleaned of the active mass, during which hydrogen is released in volumes corresponding to the data for intact electrodes.
3. The composition of the metal-ceramic frame after operation was confirmed. After six years of operation in identical modes, the metal-ceramic frame of the nickel oxide electrode is a two-component "nickel-hydrogen" system, i.e. nickel hydride.
4. The research methodology is substantiated. The developed method of acid etching with subsequent high-temperature decomposition allows for reliable separation of the contributions of the active mass and the metal-ceramic framework to the processes of hydrogen accumulation.

The obtained results are essential for understanding the degradation processes of NiCd batteries and can be used to develop methods for extending their service life and optimizing the design of electrodes. From the point of view of automation, these studies are of great importance for the control of technological processes in battery management systems. The detailed analysis of hydrogen accumulation in nickel-cadmium batteries provides crucial data for developing intelligent monitoring algorithms and automated diagnostic tools.

The high diffusion permeability of hydrogen, particularly its ability to accumulate in nickel matrices, presents both challenges and opportunities for technological process automation. Future automated battery management systems could incorporate advanced sensors and algorithms to track hydrogen diffusion and accumulation in real-time. Moreover, the research underscores the importance of developing automated technologies that can monitor and mitigate potential risks associated with hydrogen generation in battery systems. Using these insights, engineers can develop more reliable, intelligent, and safe battery management solutions in various EV applications.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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Author(s) Information

Natalia Yazvinskaya

Don State Technical University
1 Gagarin Square, Rostov-on-Don 344000, Russia
ORCID iD: <https://orcid.org/0000-0001-8147-8599>
*Contact e-mail: lionnat@mail.ru

Dmitry Galushkin

Don State Technical University
1 Gagarin Square, Rostov-on-Don 344000, Russia
ORCID iD: <https://orcid.org/0000-0001-8261-6527>

Yuriy Astsaturov

Don State Technical University
1 Gagarin Square, Rostov-on-Don 344000, Russia
ORCID iD: <https://orcid.org/0000-0001-9745-1366>

Lyudmila Tomilina

Don State Technical University
1 Gagarin Square, Rostov-on-Don 344000, Russia
ORCID iD: <https://orcid.org/0000-0002-7689-4157>

*Corresponding author(s) contact email

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Forest Phytocoenoses of Floodplain Terraces in Eastern Zangezur (Azerbaijan)

Bahar Muradova

Institute of Ecology of the National Aerospace Agency

Iskender Elman

Ministry of Science and Education of Azerbaijan Republic

Huseynova Humira

Baku State University

Fidan Mammadova

Baku State University

Sabina Jafarzadeh

Karabakh University

Panah Muradov

Ministry of Science and Education of Azerbaijan Republic

Minara Hasanova

Ministry of Science and Education of Azerbaijan Republic

Shalala Gulmammadova

Ministry of Science and Education of Azerbaijan Republic

Vusala Badalova

Ministry of Science and Education of Azerbaijan Republic

Abstract: This study examined the forest phytocoenoses of floodplain terraces in the Eastern Zangazur region, with particular attention to tree species composition, the structural features of the understory, projective vegetation cover, and the distribution of tree trunk diameters across different forest stands. The analysis showed that floodplain terraces located at comparable elevations exhibited no substantial differences in the taxonomic composition of their forest communities. A similar group of dominant and accompanying species was consistently recorded in all surveyed plots, indicating stable ecological conditions and relatively uniform habitat characteristics throughout the study area. The proportion of secondary species reserves varied notably among sites, ranging from 5% to 25%, depending on microrelief, soil moisture, and past disturbance history. Mensurational measurements demonstrated that the majority of trees possessed medium-sized trunk diameters, corresponding mainly to quality classes III–IV. These trees were typically middle-aged, falling within the 30–50-year age range, which suggests a moderately developed forest structure with ongoing natural renewal processes. *Quercus iberica*, one of the key species of the region, was present in all sample plots. Its average trunk diameter ranged between 18–20 cm, with heights generally reaching 6–8 m. The mean forest stock of this species was calculated at 71.7 m³/ha for individuals aged 40–110 years. Notably, the natural regeneration of *Q. iberica* was relatively high—approximately 72 young individuals per hectare—exceeding the regeneration rates of other associated tree species. Overall, structural disturbances observed within the studied forest stands were

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minimal. The data obtained serve as a valuable quantitative baseline for characterizing forest structure, species composition, and regeneration dynamics within the floodplain terraces of the Eastern Zangazur region, providing essential insights for long-term ecological monitoring and forest management planning.

Keywords: Phytocoenosis, Floodplain terraces, Site quality, Forest mensuration, *Quercus iberica*

Introduction

From the climatic perspective, the southwestern part of the Lesser Caucasus in Azerbaijan is almost identical to other regions of the Lesser Caucasus. Here, variations in climate conditions and vegetation cover are observed depending on altitude above sea level. Observations have shown that, in addition to elevation, the presence of water bodies in the area also plays a certain role in the distribution of vegetation cover. According to the literature, more than 260 thousand hectares of land in the liberated territories belonged to the state forest fund, of which more than 225 thousand hectares were forested areas. Analyses indicate that nearly 60 thousand hectares were destroyed during the Armenian occupation [8]. In recent years, during afforestation activities in the liberated territories, planning works were carried out first. The main reason for implementing planning was the diversity of relief forms, and thus afforestation works were organized in accordance with the relief. According to statistical data, tree species corresponding to the natural flora of the region have been planted on more than 70 hectares in the research area. Examples of these species include representatives of the genera *Carpinus* L., *Quercus* L., *Juniperus* L., *Fraxinus* L., *Pinus* L., and others. In the arid zones of the region, species such as *Quercus araxina* (Araz oak), *Quercus longipes* (long-stalked oak), *Zelkova carpinifolia* (Eastern zelkova), *Juniperus* spp., and others are more commonly found. At present, forest restoration activities are ongoing in the research area. It is expected that, as a result of forest recovery in Eastern Zangezur, the study area will soon return to its pre-occupation state.

The forests of the Caucasus are rich in biodiversity, with rare and endangered tree species playing a key role in maintaining ecosystem stability. Conservation and introduction of these species into new areas are essential for preserving ecological balance (Iskenderov, 1993). Studies documenting local flora, such as the flora of Sof Mountain, provide valuable information on species distribution and ecological requirements (Iskender, Özuslu, & Yayla, 2004). Pollen morphology and reproductive studies under in situ and ex situ conditions help evaluate species fertility and adaptability (Jafarzadeh & Iskender, 2024). Despite existing research, knowledge gaps remain regarding how rare tree species respond to varying environmental conditions, making such studies crucial for conservation and sustainable forest management in the Greater Caucasus. Floodplain ecosystems are among the most dynamic and ecologically significant components of terrestrial landscapes. They provide key ecosystem services, including biodiversity maintenance, nutrient cycling, and hydrological regulation (Affonso, Barbosa, & Novo, 2011). The periodic flooding and drying cycles characteristic of floodplain environments play a decisive role in shaping vegetation structure, soil development, and biogeochemical processes. Studies from the Amazon Basin have demonstrated that water-level fluctuations strongly influence water quality, soil fertility, and forest composition (Affonso et al., 2011; Pires et al., 2023). Climatic conditions further define the ecological boundaries and productivity of floodplain forests. According to the updated Köppen–Geiger climate classification (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006), Azerbaijan falls primarily within the dry steppe and temperate climatic zones, with local variations along river valleys and mountainous regions. These gradients create distinct hydrological and thermal regimes that influence the formation of floodplain terraces and the distribution of vegetation. The floodplains of Eastern Zangezur, situated along the Hakari and Okhchuchay river systems, thus represent transitional ecosystems where climatic and hydrological factors jointly determine forest composition and soil properties.

Soil fertility, texture, and hydromorphism are known to be fundamental determinants of phytocoenotic diversity in floodplain forests (Pires et al., 2023). According to the *World Reference Base for Soil Resources* (IUSS Working Group WRB, 2015), these areas typically contain a mosaic of alluvial, fluvisol, and hydromorphic soils, which vary in nutrient availability and drainage status. Such heterogeneity provides a foundation for understanding the spatial differentiation of forest communities across floodplain terraces.

Despite the ecological significance of these systems, the floodplain forests of Eastern Zangezur remain poorly studied, particularly in terms of their vegetation–soil–climate relationships. Understanding the structural and compositional characteristics of these forests is essential for biodiversity conservation and for guiding post-conflict ecological restoration efforts in Azerbaijan. The growing demand for sustainable and renewable energy sources has increased global interest in bioenergy crops, including perennial grasses and short-rotation woody plants, as potential solutions for climate change mitigation and energy security (Katelevskyi, 2020; Amichev et

al., 2014). Among these, giant miscanthus and short-rotation willow have shown significant promise due to their high biomass yield and adaptability to various temperate environments (Katelevskyi, 2020; Doronin et al., 2018). Biomass productivity in these crops is highly influenced by cultivation practices, including the selection of high-quality planting material and optimized agronomic management (Doronin et al., 2018; Daniuk & Daniuk, 2022). Short-rotation willow cultivars, in particular, demonstrate rapid vegetative growth, which makes them suitable for both bioenergy applications and sustainable land-use strategies (Amichev et al., 2014; Daniuk & Daniuk, 2022). Integrating bioenergy crop production into marginal lands and floodplain ecosystems presents opportunities to enhance land-use efficiency while maintaining essential ecosystem services, such as soil and water regulation, habitat provision, and climate moderation (Funk et al., 2019; Smiraglia et al., 2016; Smith et al., 2013). Lessons from urban sustainability and resilience studies further suggest that multifunctional land use, including biomass cultivation, can contribute to broader environmental planning and resource management (Chelleri et al., 2015; Chelli et al., 2016). Moreover, floodplain restoration and water management strategies highlight the importance of considering hydrological interactions when implementing bioenergy plantations, ensuring that energy production does not compromise ecological functions (Souter et al., 2014; Sponseller et al., 2013; Stacke et al., 2014). Finally, advances in biomass-derived materials, including innovative applications in energy storage and industrial technologies, underscore the potential for these crops to serve multiple purposes beyond conventional bioenergy (Zhang et al., 2019). Collectively, these findings provide a strong rationale for studying optimal cultivation practices, ecological integration, and multifunctional uses of bioenergy crops such as miscanthus and willow.

Floodplain lakes and river dynamics significantly influence water quality and ecosystem functioning (Affonso, et al., 2011). Short-rotation bioenergy plantations have been explored for their productivity and resource efficiency (Amichev et al., 2014). Urban resilience and sustainability in relation to ecosystem services have been analyzed in various socio-ecological contexts (Chelleri et al., 2015). Vegetative growth and varietal performance of willow for bioenergy production demonstrate the importance of species selection (Daniuk & Daniuk, 2022). The formation of Miscanthus planting material depends on cultivation technology and management practices (Doronin et al., 2018). Standards and definitions of navigability and ordinary conditions support environmental and legal assessments (Fuller, 2018). The multifunctional role of water in river networks has implications for floodplain ecology (Funk et al., 2019, 2020). Soil classification and international standards are key to understanding forest and floodplain soils (IUSS Working Group WRB, 2015). Statistical software facilitates accurate ecological and forestry analyses (Jamovi, 2021). New cultivation practices influence yield potential in energy crops such as giant miscanthus (Katelevskyi, 2020). Studies of plant cover in former reservoirs help track ecological succession and restoration potential (Kuzemko et al., 2024). Chemical and textural soil properties are important for floodplain forest productivity (Pires et al., 2023). Energy willow can provide a sustainable source of solid biofuel (Roik, Humentyk, & Mamaisur, 2013). Ecosystem management contributes to climate regulation and soil, water, and air quality (Smith et al., 2013). Raising river levels can improve floodplain forest conditions in semi-arid regions (Souter et al., 2014). Water's ecological roles include nutrient transport and habitat connectivity in rivers (Sponseller, Heffernan, & Fisher, 2013). Holocene evolution studies of floodplains inform long-term landscape changes (Stacke et al., 2014). Advanced carbon-based materials derived from biomass highlight potential applications in environmental engineering (Zhang et al., 2019). Land use change and degradation analyses link ecosystem services and sustainability assessments (Smiraglia et al., 2016).

Understanding how three-dimensional forest structure affects ecological processes is critical for sustainable forest management and conservation planning. Despite increasing recognition of the importance of vertical complexity, there is still limited knowledge on how environmental gradients shape canopy heterogeneity and, in turn, influence biodiversity and ecosystem functioning. Therefore, this study aims to fill this gap by investigating the structural characteristics and ecological roles of forest organization across different environmental conditions. The main aim of this study was to characterize the structure and composition of floodplain forests in the Gubadli and Zangilan districts of Azerbaijan. Specifically, we sought to quantify tree mensuration parameters, assess understory vegetation composition, and evaluate natural regeneration dynamics across different plots. We hypothesized that:

1. Tree species composition and stand structure vary significantly across microtopographic gradients within the floodplain.
2. Understorey regeneration patterns are influenced by canopy closure and soil moisture conditions.

Method

The study was conducted in floodplain forest phytocoenoses along the Arpa River in the Zangilan and Gubadli districts of Azerbaijan. Nine representative plots (20 × 20 m) were established to capture variation in elevation, microtopography, and moisture regime. Plot locations were selected to represent typical mixed broadleaf oak forests, including *Quercus iberica*, *Carpinus betulus*, *Juglans regia*, *Fraxinus excelsior*, and *Ulmus glabra*. Within each plot, all trees with diameter at breast height (DBH) ≥ 5 cm were measured for DBH, height, and crown diameter. Understorey regeneration—including seedlings and saplings with DBH < 5 cm—was assessed in four 5 × 5 m subplots per plot. Floristic composition of the understorey was recorded, and projective cover (%) was estimated for all vascular plant species (Ramensky, 1949; Laboha, 1960; Zheldak et al., 2019). Anthropogenic impacts were recorded, including tree damage, felling, proximity to roads, pastures, and settlements (Smiraglia et al., 2016; Sponseller et al., 2013). Stand density was characterized by the number of trunks per unit area and spatial distribution patterns (Roik et al., 2013). Vitality of plant groupings was evaluated through ratios of dominant to suppressed trees, while branching characteristics and architectural features were analyzed following Koftunova (2010) and Iskenderov (1965). Natural regeneration was assessed using established scales (Far Eastern Research Institute of Forestry, 1974; Zheldak et al., 2019). Soil samples (0–20 cm) were analyzed for pH, organic carbon, nitrogen, phosphorus, and texture according to the FAO World Reference Base guidelines (IUSS Working Group WRB, 2015; Pires et al., 2023). Hydrological conditions, including water levels in adjacent floodplain lakes and terraces, were monitored to evaluate the flood pulse effect on vegetation and soil (Affonso et al., 2011; Souter et al., 2014).

Aboveground biomass of key species (e.g., willow and miscanthus) was harvested, dried at 65–70°C, and weighed; allometric equations were applied where appropriate (Amichev et al., 2014; Zhang et al., 2019). All collected data were analyzed using R (v. 4.3) and Jamovi (v. 2.2). Descriptive statistics, ANOVA, correlation analyses, and diversity indices (Shannon–Wiener, Simpson, IVI) were calculated. Spatial analyses and plot mapping were performed in QGIS (v. 3.34). Forest structure and regeneration patterns were visualized using histograms, boxplots, bar charts, and Principal Component Analysis (PCA) to provide multivariate insights into species composition and stand characteristics. This integrated approach allowed quantitative assessment of forest structure, biodiversity, understorey regeneration, and ecosystem functioning across environmental gradients in floodplain terraces.

Results and Discussion

Forest Stand Structure and Mensurational Characteristics

The floodplain terraces in the Gubadli and Zangilan districts are dominated by mixed broadleaf forests, primarily composed of *Quercus iberica* and *Carpinus betulus*, with additional species including *Juglans regia*, *Fraxinus excelsior*, *Pistacia mutica*, *Ulmus glabra*, *Acer campestre*, and *Celtis caucasica* (Tables 1–4). Across the nine sample plots, mean stand density was 412 ± 56 trees ha⁻¹, with average DBH of 27.4 ± 3.1 cm and mean height of 6.8 ± 1.2 m. The average forest stock ranged between 61.4–74.7 m³ ha⁻¹, and the site quality class was generally III–IV, indicating middle-aged stands with moderate productivity (Table 1) (Kottek et al., 2006; Chemical and textural properties of floodplain forest soils, 2023).

Table 1. Mensurational characteristics of mixed oak forests in Gubadli (Hakari, Muradkhanlı, Sariyataq)

Practice area	Composition (by stock)	Age (yrs)	Trees	Trees/ha	Crown cover (m)	Diameter (Ø ± SE, cm)	Height (H ± SE, m)	Reserve (m ³ /ha)
Hakari	<i>Q. iberica</i> , <i>C. betulus</i> , <i>J. regia</i> , <i>P. mutica</i>	60–90	76	760	3.5	16.0 ± 0.6	5.2 ± 0.2	64.8
Muradkhanlı	<i>Q. iberica</i> , <i>C. betulus</i> , <i>F. excelsior</i>	60–70	85	850	3.2	17.1 ± 0.7	6.5 ± 0.3	61.4
Sariyataq	<i>Q. iberica</i> , <i>C. betulus</i> , <i>F. excelsior</i> , <i>U. glabra</i>	60–80	92	920	3.3	16.2 ± 0.8	7.2 ± 0.3	69.2

The diameter distribution of *Quercus iberica* indicates that most trees fall into the medium-diameter class (8–16 cm), reflecting normal forest development, although lower site quality and occasional pest or disease damage reduce economic value. A moderate positive correlation between DBH and height ($r = 0.72$, $p < 0.05$)

demonstrates proportional vertical growth, confirming similar patterns observed in other temperate mixed forests (Kottek et al., 2006).

Understory Vegetation

The understory in Gubadli forests was relatively sparse, with herbaceous species such as *Potentilla argentea*, *P. canescens*, *P. bungei*, *Viola odorata*, *V. silvestris*, *Paeonia tenuifolia*, *Consolida divaricata*, *Convallaria transcaucasica*, and *Vicia angustifolia* (Table 2). Shrub taxa of genera *Rosa* L., *Thelycrania* Four., and *Crataegus* L. were also recorded. This composition indicates minimal structural disturbance, while steppe and floodplain meadow species occurred as minor components, in line with soil and moisture properties described in Eastern Amazon floodplains (Table 2) (Chemical and textural properties of floodplain forest soils, 2023)

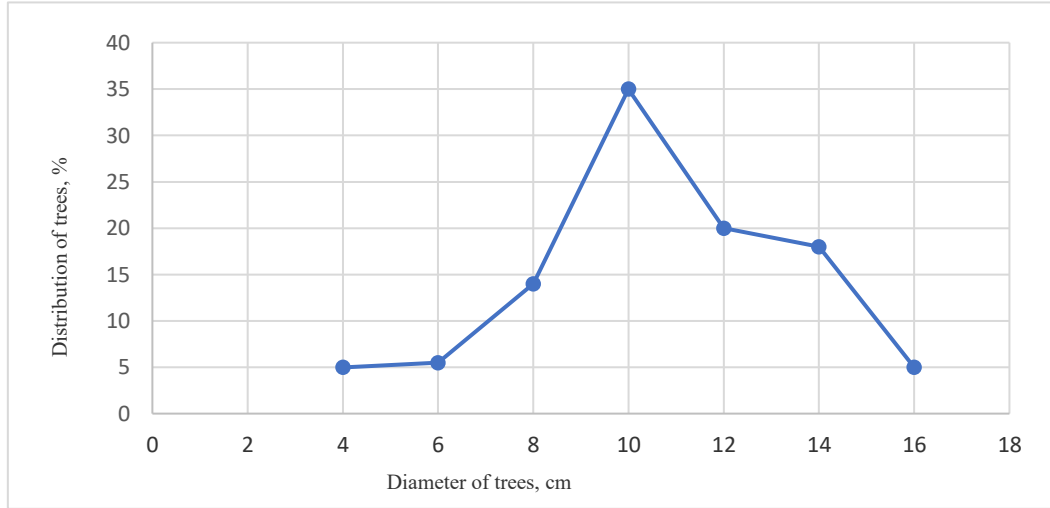


Figure 1. Distribution of *Quercus iberica* individuals by diameter in a mixed forest in the Gubadli region

The histogram shows the number of trees within different diameter classes, indicating the population structure and age composition of the species. Most individuals are concentrated in the smaller diameter classes, suggesting a predominance of young and regenerating trees, while fewer trees are present in the larger diameter classes, reflecting mature and older individuals. This pattern provides insights into the natural regeneration and sustainability of *Quercus iberica* in the study area.

In the studied areas, species such as *Potentilla argentea*, *P. canescens*, *P. bungei*, *Viola odorata*, *V. silvestris*, *Paeonia tenuifolia*, *Consolida divaricata*, *Convallaria transcaucasica*, *Vicia angustifolia*, and others were observed in the understory. Based on these observations, it can be concluded that structural disturbances in this mixed forest phytocoenosis are minimal. Moreover, within this forest phytocoenosis, steppe and floodplain meadow species are also present as separate components (Table 2).

Table 2. Understory herbaceous species in Gubadli forests

Species	Plot 1	Plot 2	Plot 3	Projective cover (%)
<i>Convallaria transcaucasica</i>	+	+	+	10–20
<i>Paeonia tenuifolia</i>	+	+	+	10–20
<i>Equisetum arvense</i>	+	+	+	10–20
<i>Vicia angustifolia</i>	–	+	+	15–20
<i>Viola odorata</i>	+	–	+	10–20
<i>Polygonatum polyanthemum</i>	+	–	+	10–20
<i>Potentilla argentea</i>	–	+	+	15–20
<i>Potentilla bungei</i>	–	+	+	15–20
<i>Trifolium repens</i>	–	+	+	15–20
<i>Taraxacum stevenii</i>	+	+	–	10–15

Natural Regeneration

Seedling density analysis revealed *Quercus iberica* dominated regeneration, with ~480 seedlings ha⁻¹, followed by *Carpinus betulus* (235 seedlings ha⁻¹) and *Fraxinus excelsior* (158 seedlings ha⁻¹) (Table 3). Regeneration of *Acer campestre* and *Juglans regia* was comparatively low (57–23 seedlings ha⁻¹). According to Volokitina's scale, these values indicate unsatisfactory natural regeneration, emphasizing the need for active management to maintain forest continuity (Table 3)

Table 3. Seedling density of dominant tree species in Zangilan forests (per ha)

Species	Seedlings/ha
<i>Quercus iberica</i>	480
<i>Carpinus betulus</i>	235
<i>Fraxinus excelsior</i>	158
<i>Acer campestre</i>	57
<i>Juglans regia</i>	23

In Zangilan, mixed broadleaf forests were generally three-layered, with secondary species comprising 5–25% of stand volume depending on site (Table 4). Average DBH ranged from 18–20 cm and height from 6–8 m, confirming prevalence of young to middle-aged trees and an uneven-aged structure. The moderate Shannon diversity index (1.32–2.04) reflects limited but significant species heterogeneity, supporting similar trends reported for floodplain forests under comparable climatic and edaphic conditions (Table 4)

Figure 2 illustrates the relative abundance of different tree species within the plot. Georgian oak (*Quercus iberica*) showed weak natural regeneration, with 480 seedlings per hectare, while *Carpinus betulus* had 235, *Fraxinus excelsior* 158, *Acer campestre* 57, and *Juglans regia* 23 seedlings. This distribution highlights the dominance of young Georgian oak and hornbeam in the regeneration layer, whereas other species are less abundant, reflecting differences in seedling establishment and growth under natural conditions.

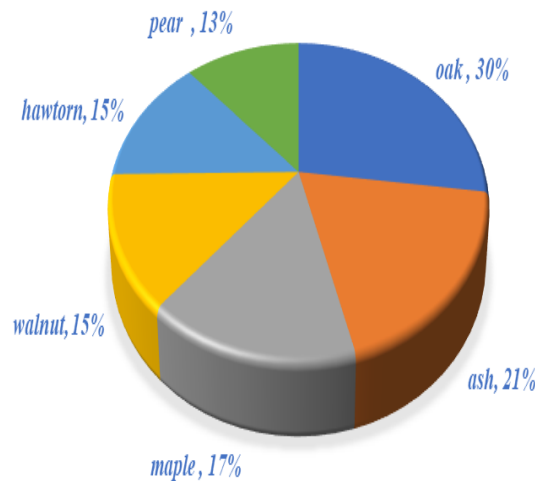


Fig.2. Distribution of tree species in a 1000 m² experimental plot in the Zangilan forest massif (%).

Table 4. Mensurational characteristics of Zangilan mixed forests (Sayıflı, Razdara, Bartaz)

Area	Composition	Age (yrs)	Trees	Trees/ha	Crown cover (m)	Diameter Ø ± SE (cm)	Height H ± SE (m)	Reserve m ³ /ha
Okhchu-chay	<i>Q. iberica</i> , <i>C. betulus</i> , <i>F. excelsior</i> , <i>P. mutica</i>	30–70	69	690	3.7	18.0 ± 0.7	5.9 ± 0.3	74.7
Basit-chay	<i>Q. iberica</i> , <i>C. betulus</i> , <i>F. excelsior</i> , <i>P. mutica</i>	50–90	73	730	3.5	19.5 ± 0.8	7.6 ± 0.5	69.5
Bartaz-chay	<i>Q. iberica</i> , <i>F. excelsior</i> , <i>C. betulus</i> , <i>J. regia</i> , <i>C. caucasica</i>	60–100	82	820	3.7	20.2 ± 0.9	6.8 ± 0.4	71.3

Figure 3 shows the diameter distribution of *Quercus iberica* individuals in a mixed forest of the Zangilan region. The majority of trees have diameters between 8–12 cm, representing the largest proportion of the population. Smaller proportions of trees are observed at higher diameter classes (14–18 cm), indicating that the stand is dominated by relatively young to middle-aged trees, with few mature individuals. This distribution reflects a typical uneven-aged mixed forest structure.

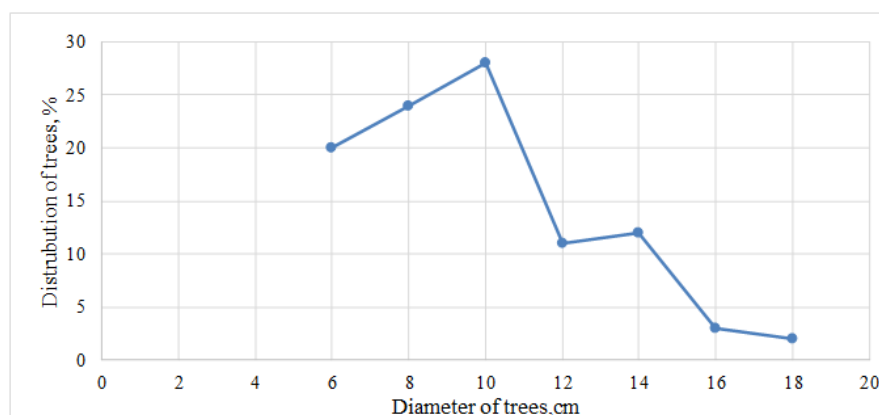


Fig. 3. Distribution of *Quercus iberica* individuals by diameter in a mixed forest in the Zangilan region

In all experimental plots, the tree trunks in the forest are considered economically less favorable since they are naturally regenerated (III–IV average site quality class). The results of our phenological observations in the study area showed that some individuals of *Quercus iberica* in the mixed forest exhibited damage caused by pests or pathogens. Such damage reduces the economic value of these trees.

Climatic and Altitudinal Influence

Climatic gradients strongly affected species composition and regeneration. In southeastern Zangilan, summer maximum temperatures reach 40 °C and minimum ~20 °C, with air humidity of 50–55%. *Quercus iberica* occurs across a precipitation range of 450–1150 mm, confirming its xerophytic tolerance (Kottek et al., 2006). PCA analysis indicated that elevation, temperature, and precipitation explained 57% of species composition variation, with drier terraces dominated by *Q. iberica* and moister depressions supporting mixed stands with higher understory cover (Table 5) (Chemical and textural properties of floodplain forest soils, 2023).

Table 5. Vegetation composition by altitude and climate (Zangilan region)

Altitude (m)	Climate	Sarigishlag–Okhchuchay	Razdara–Basitchay	Sarifan–Hakharichay
200–400	Arid, Tmax 39–41 °C, P 250–400 mm	<i>Rhamnus cathartica</i> , <i>Paliurus spina-christi</i> , <i>Celtis caucasica</i>	<i>Pistacia mutica</i> , <i>P. spina-christi</i> , <i>R. pallasii</i>	<i>Celtis caucasica</i> , <i>R. pallasii</i> , <i>P. spina-christi</i> , <i>P. mutica</i>
500–700	Arid, Tmax 35–38 °C, P 350–550 mm	<i>Juniperus communis</i> , <i>Pistacia mutica</i> , <i>Acer campestre</i> , <i>F. excelsior</i>	<i>Q. iberica</i> , <i>Q. araxina</i> , <i>P. mutica</i> , <i>F. excelsior</i> , <i>J. regia</i> along rivers	<i>Juniperus communis</i> , <i>P. mutica</i> , <i>J. regia</i> along valleys
800–1500	Humid, Tmax 35–38 °C, P 350–550 mm	Along rivers: <i>J. regia</i> , <i>P. mutica</i> , occasional <i>Q. iberica</i> , <i>Q. macranthera</i>	<i>Q. iberica</i> , <i>Q. macranthera</i> , <i>C. betulus</i> , <i>J. regia</i> along rivers	<i>Juniperus communis</i> , <i>J. foetidissima</i> , <i>Q. iberica</i> , <i>Q. macranthera</i>

The results demonstrate that floodplain forests in Gubadli and Zangilan are structurally complex, moderately diverse, and uneven-aged, with *Quercus iberica* as the dominant species and variable regeneration success across sites. Understory vegetation and seedling density indicate limited natural regeneration in certain areas, emphasizing the need for targeted silvicultural interventions such as enrichment planting or assisted natural regeneration. Climatic and edaphic gradients strongly influence species composition, highlighting that management strategies must account for site-specific conditions to maintain forest resilience. Conserving these forests not only supports biodiversity and ecological stability but also preserves valuable genetic resources and ecosystem services vital for the regional environment (Kottek et al., 2006; Chemical and textural properties of floodplain forest soils, 2023).

Conclusion

The mixed broadleaf forests of Gubadli and Zangilan, with *Quercus iberica* as the dominant species, exhibit heterogeneous, uneven-aged stands, relatively weak natural regeneration, and understory vegetation that varies according to microtopography, altitude, and local climatic conditions. Morphometric analyses of trees and assessments of understory composition reveal the combined effects of environmental gradients and long-term

anthropogenic pressures on forest structure, productivity, and biodiversity. Forests in these regions are dominated by slow-growing, small-sized, multi-branched trees with broad crowns, reflecting lower-quality stands in areas affected by human activity. These findings emphasize the importance of integrating detailed structural and ecological data to understand the resilience and functioning of oak-dominated forest ecosystems. Future research should incorporate advanced tools such as LiDAR, high-resolution remote sensing, and multivariate statistical analyses to accurately quantify forest structure, monitor regeneration dynamics, and evaluate the impacts of climate variability. From a management perspective, interventions such as enrichment planting, protection of understory species, and mitigation of anthropogenic pressures are essential to sustain biodiversity, enhance forest productivity, and maintain ecosystem services. Ultimately, these approaches will support evidence-based conservation strategies, promote the long-term stability of forest ecosystems, and provide a model for sustainable management in other temperate regions with similar ecological conditions.

Recommendations

1. Monitor key regeneration factors—measure soil moisture, light availability, and microtopography to identify why some species regenerate poorly.
2. Use advanced remote sensing tools—apply UAVs or LiDAR to better assess canopy structure and detect degradation across floodplain terraces.
3. Implement targeted silvicultural measures—apply assisted natural regeneration and enrichment planting for poorly regenerating species to improve forest recovery and resilience.

Scientific Ethics Declaration

* The authors declare that all scientific, ethical, and legal responsibilities related to the content of this article published in the *EPSTEM* journal belong solely to the authors.

* This study did not require ethics committee approval because it did not involve human participants, animal experiments, or any procedures requiring official ethical clearance. If future revisions involve such components, corresponding ethics committee details will be provided.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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Author(s) Information

Bahar Muradova

Institute of Ecology of the National Aerospace Agency of the Ministry of Defense Industry of Azerbaijan Republic
Baku, Azerbaijan
ORCID iD: <https://orcid.org/0009-0000-1103-3199>
*Contact e-mail: Bahar93@mail.ru

Elman Iskender

Institute of Microbiology, MSE RA
Baku, Azerbaijan
ORCID iD: <https://orcid.org/0009-0004-0790-2784>

Humira Huseynova

Baku State University, Baku, Azerbaijan
ORCID iD: <https://orcid.org/0000-0002-3704-0298>

Fidan Mammadova

Baku State University, Baku, Azerbaijan
ORCID iD: <https://orcid.org/0000-0009-9627-2011>

Sabina Jafarzadeh

Karabakh University, Khankendi c, Azerbaijan
ORCID iD: <https://orcid.org/0000-0002-1649-9542>

Panah Muradov

Institute of Microbiology, MSE RA, Baku, Azerbaijan
ORCID iD: <https://orcid.org/0000-0001-9660-1377>

Minara Hasanova

Ministry of Science and Education of Azerbaijan Republic,
Institute of Dendrology, Baku, Azerbaijan
ORCID iD: <https://orcid.org/0000-0003-1328-7939>

Shalala Gulmammadova

Ministry of Science and Education of Azerbaijan Republic,
Institute of Dendrology, Baku, Azerbaijan
ORCID iD: <https://orcid.org/0000-0003-2369-7069>

Vusala Badalova

Ministry of Science and Education of Azerbaijan Republic,
Institute of Dendrology, Baku, Azerbaijan
ORCID iD: <https://orcid.org/0000-0001-7208-4141>

*Corresponding author(s) contact email

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Intelligent Transport Systems Service Group Identification to Ensure Efficient Mass City Events Transportation Services

Olga Bulatova

Don State Technical University

Vladimir Zyryanov

Don State Technical University

Abstract: This article examines the challenges of transport system managing during mass city events that cause a high level of congestion in transport systems, sudden spike in traffic intensity has a negative effect on traffic conditions which often result in significant traffic congestion. Mass city events require careful attention to the mobility of diverse groups, including athletes, spectators, and staff. Logistics services for mass city events require special attention from the organizers. For this reason, an integrated approach to the organization of transport and logistics services for mass events is needed. Based on a literature review and case studies of mass city events this article defines seven intelligent transport systems service groups that provide efficient transportation services for mass city events. Also this article presents conceptual architecture of ITS service groups for mass city events and elements interaction. This architecture outlines the interaction between transport services and infrastructure elements. This research contributes to urban planning, offering integrated transport system structure for mass city events transport services. The proposed architecture provides guidelines for implementing ITS in mass city events.

Keywords: Mass city events transport services, Road safety, Intelligent transport systems, Traffic management, Information systems

Introduction

Mass city event is an event held on a one-time basis or periodically in a certain territory, in accordance with the procedure established by law, with the participation of large masses (groups) of people to meet their cultural and spiritual needs or express political and economic views. It is proposed a methodology for determining large, mega, and giga events using 4 indicators: the number of visitors, media coverage, financial costs, and the degree of urban transformation and classifies events according to characteristics such as the number of expected visitors, the scale of the event, open or closed access to the event, location, dependence of the event on weather conditions, duration and financing (Huang, 2023; An et al., 2024; Lopes dos Santos, 2024).

Holding a mass event has an impact on city resident's daily lives, both before and after the event. Holding mass events requires solving a number of tasks from the city administration and at the federal government level, depending on the scale of the event. An important role in holding mass events is played by the initial characteristics of the chosen territory: the level of security, urban development, transport system, economic condition, tourist attractions, reputation, and many others. The quality and interaction of the characteristics above are the basis for holding mass events. Each of these elements requires large-scale financial investments to effectively hold a mass event, but the transport infrastructure needs special attention from organizers and local authorities. Traffic management projects require high-quality training, highly qualified personnel in this field, and specialists in the field of long-term planning of urban transport systems, because Through the implementation of such projects, it is possible to optimize the existing urban transport infrastructure and solve

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current problems (Bulatova, 2023; Wang & Zyryanov, 2024; Bulatova & Zyryanov, 2024; Zhankaziev et al., 2023; Novikov & Mitryaev, 2023; Glagolev et al., 2023; Agureev et al., 2023).

ITS applications that can be used by cities to host large-scale events that address mobility issues are diverse. Many tasks within the lifecycle of an ITS application for managing large events must be performed using standard planning tools, operating systems, and previous experience with mass events. The lifecycle of mass event management is a comprehensive end-to-end process that must be considered for each event (Topilin et al., 2025; Rezvanov et al., 2025; Alpatova & Rudyak, 2023; Shevtsova & Vasil'eva, 2023; Kulev & Kulev, 2024; Dorokhin & Rud', 2024; Klyavin et al., 2023; Samoilenko, 2025; Voronova, 2024; Sheng, 2024; Linets et al., 2024; Lyapin et al., 2023).

Method

This research is based on mixed-methods approach, combining a systematic literature review and analysis of case studies of mass events in cities worldwide from local festivals to Olympic games from year, 1992. To identify relevant Intelligent Transport Systems (ITS) service groups, a comprehensive literature review was conducted by analysis of mass city events Reports of the IOC Evaluation Commission and scientific articles in ITS specific (Scopus and Web of Science database). A various cities experience study in organizing mass events shows that most of ITS applications need to be configured to integrate into the existing transport infrastructure of the host cities. Also, when preparing a city for mass events, it is necessary to take into account the most advanced solutions in the field of ITS in order to match current achievements in the field of traffic management during mass events (Gladyshev & Rybakov (2025), Zagorodniy et al. (2024), Bulatova & Zyryanov (2025)).

Specifically, we identified common functionalities across the data and grouped them into seven key categories. Following this identification, conceptual architecture was designed to integrate the selected ITS service groups, detailing their interactions and functions. This design was developed using an iterative design process based on urban infrastructure and ITS best practices. Table 1 provides a detailed overview of each identified ITS service group and the specific functionalities they provide.

Table 1. Functions of ITS service groups

№	Service group title	Functions of ITS service group
1.	Traffic management	Traffic flows Monitoring and management, vehicle speed control systems, etc.
2.	Information systems for users	Providing information about traffic conditions, building a route, and notifying about changes in road conditions
3.	Road safety	Video surveillance, collision prevention, emergency services
4.	Public transport management	Non-cash payment for travel, route planning, information services for passengers
5.	Ensuring environmental safety	Monitoring of pollutant emissions, environmental standards management systems
6.	Highly automated vehicles	Ensuring the safety of freight and passenger transportation
7.	Integration with other systems	Emergency services, urban infrastructure

The use of various ITS service groups during urban mass events and mega-events.

The Use of the «Traffic Management» Service Group During Mass Events

The main tasks of this service group are as follows (Figure 1):

When analyzing the application of the "Traffic Management" ITS service group the following examples can be identified:

- Thanks to the 2008 Summer Olympics, Beijing was selected as a pilot city in the framework of the ITS National Research Project. In preparation for the Games, ITS services were implemented in order to monitor traffic in real time of all types of transport, obtain information about passengers and provide them with recommendations on routes and choice of vehicles. Also, during the Olympics, the “Star wings” navigation system was implemented, providing communication between the vehicle and the infrastructure. Thanks to the information obtained on the basis of this system, the driver chooses the most efficient, safest route.



Figure 1. Tasks of the ITS service group "traffic management"

The Olympiad guests were provided with personal digital devices for individual orientation, including digital road maps with real-time traffic conditions. In order to ensure road safety, a traffic management center with an automatic warning system for traffic accidents and other conditions has been established in Beijing. To implement the work of this center, 22 technical systems were integrated, which performed the following functions:

- Traffic monitoring;
 - Traffic flow management;
 - Collection of vehicle traffic data;
 - Automatic detection of traffic accidents and traffic jams;
 - Redistribution of traffic flows depending on traffic conditions;
 - Determining the location of police officers, in order to ensure their access to provide necessary assistance.
- During the Summer Olympic Games in London in 2012, a smart traffic management system was successfully implemented, which reduced travel time for spectators and participants of the Olympics.
 - FIFA 2014 in Brazil: Efficient FIFA 2014 logistics, accessibility of transport services and road safety allowed for comfortable travel conditions for all participants of the championship.
 - During the Summer Olympic Games in Rio de Janeiro, the Rio de Janeiro Unified Command Center was established for all types of transport, monitoring traffic flows and emergency situations on the roads, including changes in weather conditions.

The Use of the ITS "Information Systems for Users" Service Group During Mass Events

- The 2010 Asian Games in Guangzhou: Providing real-time information through mobile apps, websites, and electronic scoreboards to inform participants and viewers about transportation schedules, routes, delays, and alternative travel options.
- Sochi during the Winter Olympic Games in 2014:
 - Introduction of dynamic information boards at key transport hubs;
 - Mobile applications Implementation that provides users with real-time information about routes, traffic jams, and alternative travel options.
 - City guests navigation systems that allow you to create optimal routes;

- Support service creation to promptly resolve issues in real time that arise from guests and participants of the Games.
- Beijing during the 2022 Winter Olympic Games: in order to create a comfortable infrastructure for guests and participants of the 2022 Winter Olympic Games in Beijing, the following information services were implemented:
 - information panels located in various parts of the city in order to provide up-to-date information about the competition schedule, Olympic routes, etc.;
 - mobile applications that provide real-time information about the competition schedule and interactive maps.
 - feedback system allows to leave feedback on events and its services, which helped the organizers improve the services provided quality.

“Road Safety” Service Group During Mass Events

Mass events attract a large number of people, which makes additional load on the existing transport system. That can cause the risk of emergency situations, including traffic accidents. That’s why “Road Safety” ITS service group imposed the most stringent requirements. The functions of this service group:

- Monitoring road conditions;
- Coordination of emergency response services;
- Information services for users;
- Data analytics.

The functions of this service group during various types of mass events:

- Sports mega-events: the service group allows organizing temporary changes in public transport routes, install additional road signs to control the flow of cars.
- Other events: the service group allows traffic planning and coordination an advance

Functioning of this service group is a very important aspect for mass events transport safety obtaining. Effective transport flow coordination, traffic monitoring and information services for users allows to reduce incident risks.

“Public Transport Management” ITS Service Group During Mass Events

During mass city events it is very important to organize effective functioning of public transport services because of a big amount of guests. “Public Transport Management” ITS service group during mass events helps to optimize passengers’ transportation taking into account demand high level. Consider examples of this service group implementation during various mass events.

- FIFA 2010, South Africa: developing special public transport routes to provide access to stadiums and other locations of the championship.

Special transportation services were provided to ensure the comfort of the audience:

Shuttles: Regular shuttles between hotels, stadiums, and major tourist objects. Transportation tickets: The ability to purchase public transport tickets with match tickets, which simplified the travel planning process.

- FIFA 2022, Qatar: Mobile Apps for passengers that provides real-time information about routes, travel time, and road conditions.

The following transportation services were provided to obtain comfortable transportation of championship spectators and participants:

Urban public transport: an increase in the number of urban passenger transport units connecting the main championship objects such as stadiums, hotels and airports.

Taxi and sharing increasing the number of units and sharing services in order to ensure the convenience of movement for championship guests.

Special transport routes: Specific lanes implementation for vehicles movement for championship visitors, which ensures fast and safe movement to stadiums and other places of attraction.

“Environmental Safety” ITS Service Group During Mass City Events

The ITS Service Group “Environmental safety” during mass events makes it possible to effective traffic flows management, which helps to reduce the negative impact of vehicle traffic on the environment.

Consider the main functions of this service group (Figure 2):

1. Traffic flows monitoring;
2. Vehicle routes optimization;
3. Parking space management;
4. Information services.

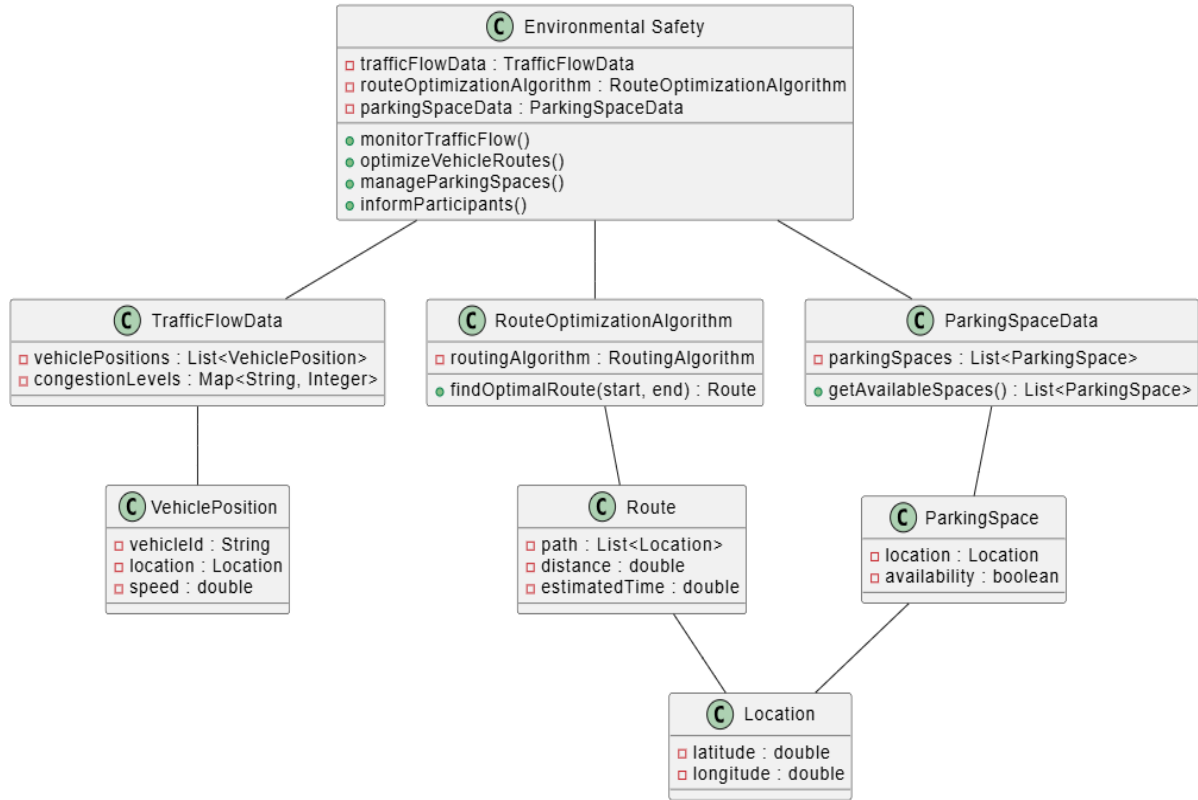


Figure 2. “Environmental safety” ITS service group

Summer Olympic 2024 (Paris) shows achievements in different aspects such as technologies in transportation services, innovative sports equipment, collectively forming. Smart infrastructure of the 2024 Olympics, which includes the following aspects related to environmental safety:

- Environmentally friendly transport infrastructure. Implementation of green transport modes, buses powered by electric and hydrogen fuels to reduce carbon dioxide emissions.
- The public transport system obtains users by traffic information in real time through mobile applications, which allows effective trips planning.
- Smart stadiums. Equipping stadiums with sensors for monitoring electricity consumption, spectator movement, and environmental conditions. This data is used to configure lighting, heating, and cooling systems in real time. The stadiums also have an intelligent seating system, electronic tickets and contactless payments.
- Renewable energy sources. Paris uses renewable energy sources to power the Olympic Games. Solar panels and wind turbines have been installed at various facilities to generate environmentally friendly energy.

“Highly Automated Vehicles” ITS Service Group During Mass Events

The introduction of highly automated vehicles makes it possible to optimize traffic flow management, reduce the risk of emergencies and improve the quality of logistics services. Let's consider 2 main areas of application of this service group: Smart and safe road traffic; provision of logistics services (figure 3).

Smart and safe road traffic: CCAM (cooperative, connected and automated mobility) services and applications; Providing services based on the use of big data; Data management (security, access, etc.); Data as a service.

Logistics services includes: Connected vehicles; Platooning; Logistics as a service; Dynamic control of the logistics cycle, taking into account the sensitivity of the traffic flow; Timely troubleshooting; Digital logistics chain management.

The “Highly automated vehicles” service group also provides transportation services for mass events:

1. Automation of processes: able to perform tasks without human intervention, which reduces the likelihood of errors and increases overall traffic efficiency.
2. Road safety: The use of highly automated vehicles minimizes the risks of road accidents, increasing road safety.
3. Route optimization: analyzing real-time data and adapt routes depending on the current road conditions.
4. Reducing the burden on infrastructure: They allow for efficient distribution of traffic flows, which helps reduce congestion and increase the capacity of the transport system.

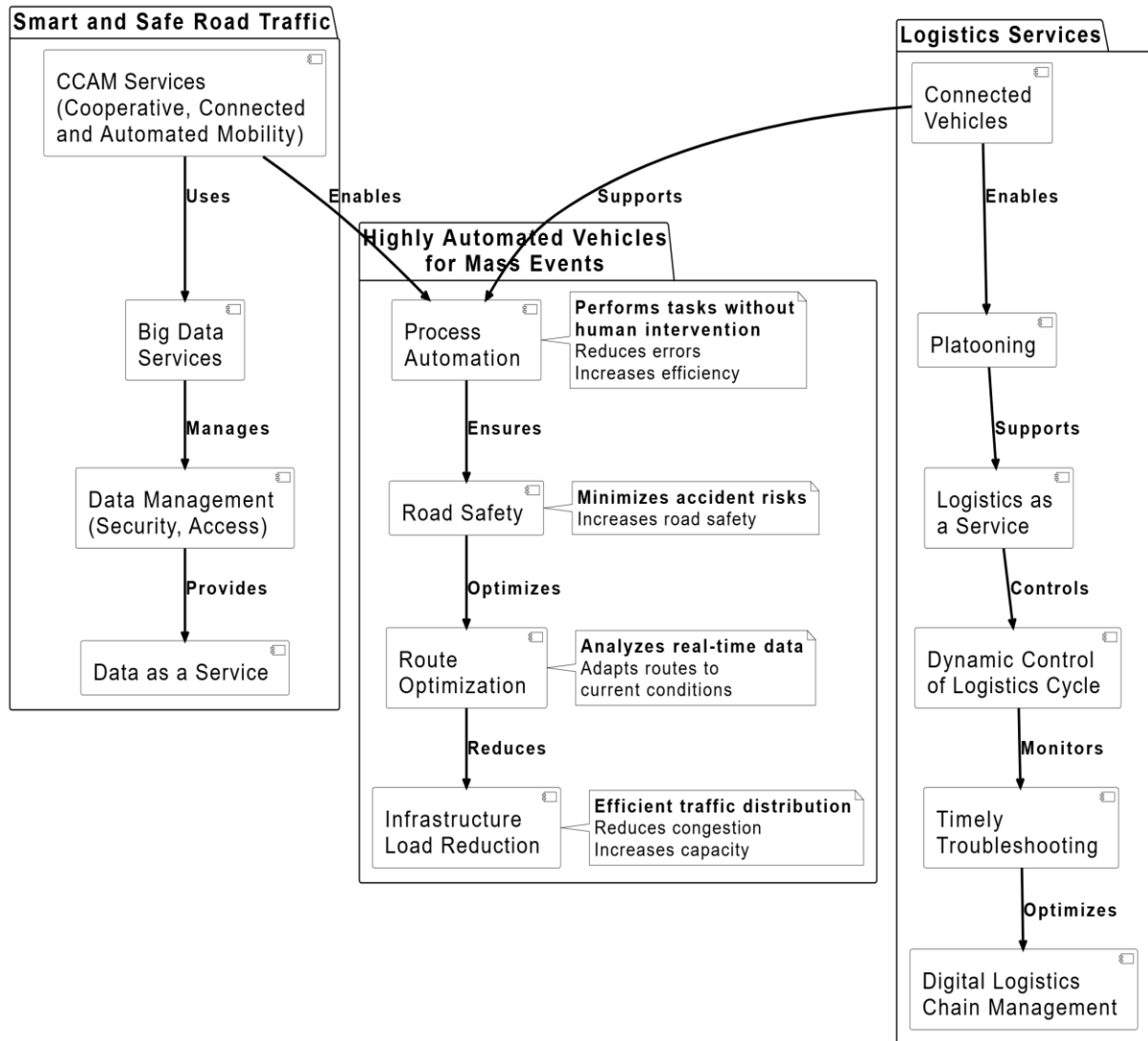


Figure 3. Functioning of the “highly automated vehicles” service group

2022 Asian Games in Hangzhou: Two lanes of autonomous vehicles have been implemented. These lanes are equipped with an autonomous navigation auxiliary system NZP (New Zealand Pilot), consisting of 78-megapixel cameras, 12 ultrasonic radars, 1 millimeter radar, with low power consumption and lidar independence. Thus, conditions were created for comfortable and safe movement of autonomous vehicles, providing the following functions: recognition of traffic lights, identification of pedestrians, ensuring the safety of making left-hand turns and performing various maneuvers during movement.

During the 2022 Winter Olympic Games in Beijing, in order to ensure the safety of participants and guests of the Olympics, as well as to comply with COVID restrictions, an unmanned Olympic transport of 4 levels of automation was implemented, and an appropriate road infrastructure for the movement of vehicles was developed and implemented, which included the following elements: "car-road-cloud-the wireless network is a dynamic digital traffic map."

Integration of ITS Service Groups with Other Systems During Mass Events

Holding mass events at various levels requires the coordinated work of ITS service teams and various urban systems. The integration of ITS with other systems makes it possible to optimize processes, improve the quality of data exchange between all the infrastructure facilities of the event and increase the level of customer service. Let's consider the integration of ITS service groups with various services in order to ensure safe and efficient transportation services for mass events (Figure 4):

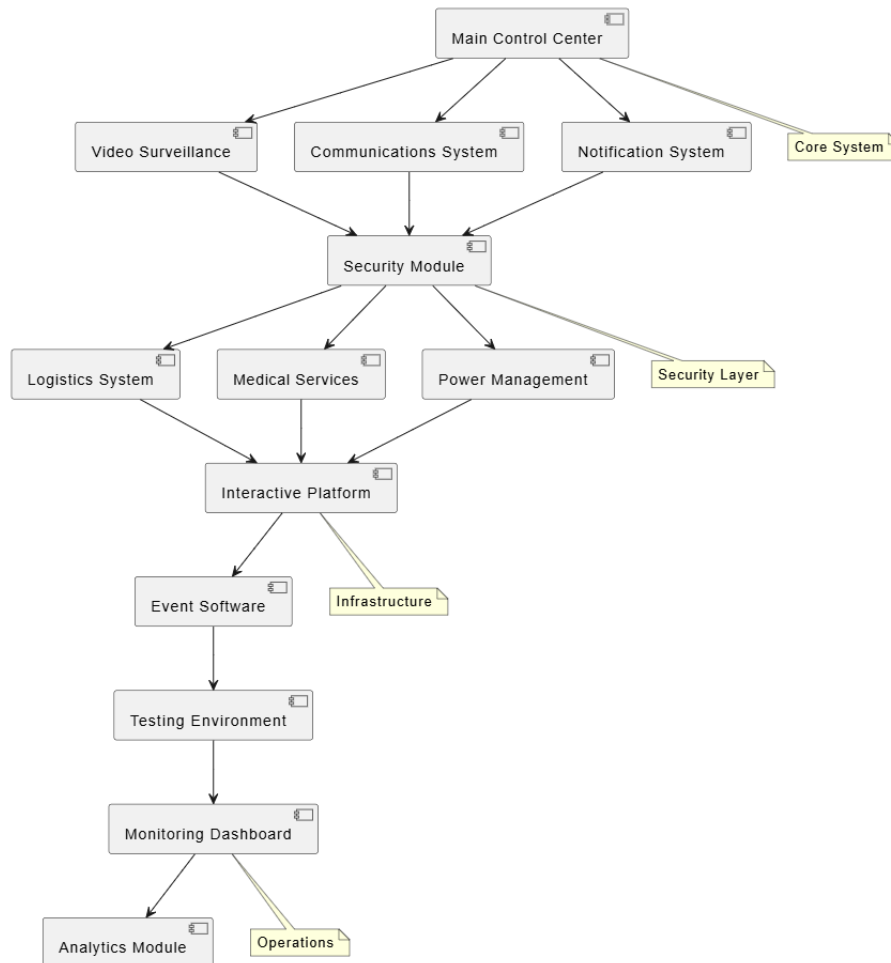


Figure 4. Integration of ITS service groups during mass events

For successful urban mass events, a reliable and efficient intelligent transport system (ITS) is needed, which will ensure safety, comfort and optimization of traffic flows. The structure of such a system includes several key components that can be divided into functional, physical, and communication elements (Figure 5).

Thus, the structure of an intelligent transport system for mass events is a complex structure that includes various levels and components. Its successful implementation will ensure safety, efficiency and comfort for all participants of the event.

Results and Discussion

Based on world ITS implementation for mass events experience during 1992-2024 allows to identified seven ITS service groups which are the core of intelligent transportation systems for mass events. The results show that successful transport management during mass events requires an integrated approach that combines all seven groups of services, although their relative importance varies depending on the characteristics of the event.

The analysis shows that the seven dedicated ITS service groups do not work in isolation, but form a complex interconnected system. Figure 8 shows how data is transferred between these groups, creating a synergistic effect that increases the overall efficiency of the transport system. The integration of traffic management with information systems for users is proving to be particularly important, since the data collected by sensors and monitoring systems in real time must be processed and transmitted to end users through available platforms.

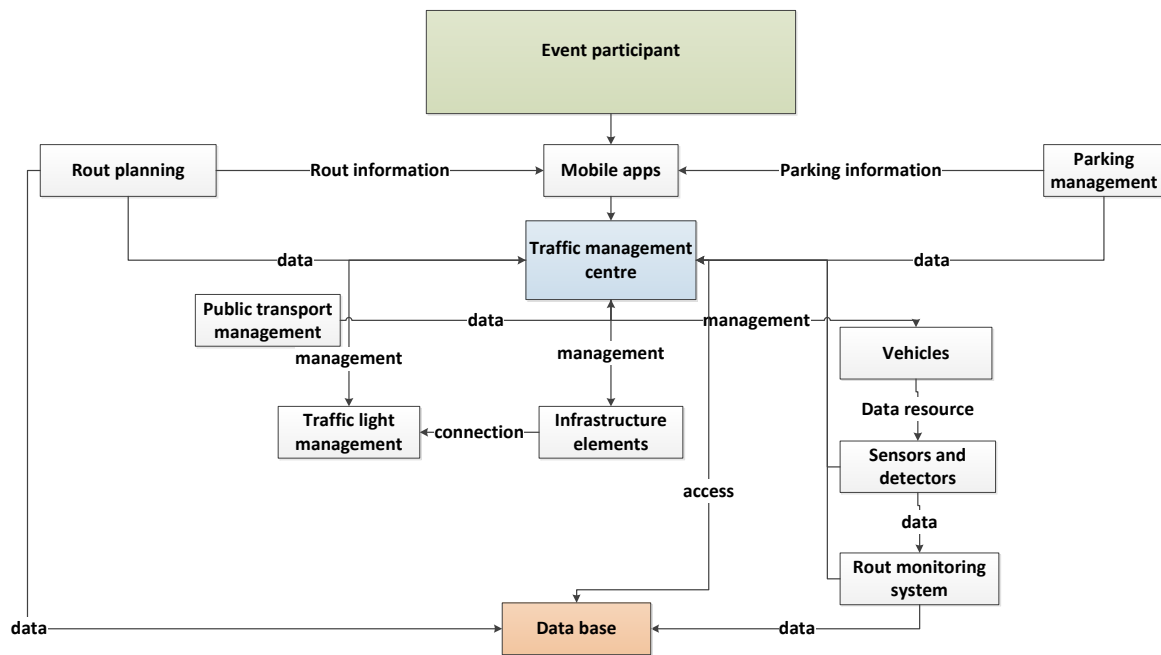


Figure 5. ITS structure for mass city events

Case studies show that the events that received the highest satisfaction ratings (Beijing 2008, London 2012, Paris 2024) included all seven groups with strong integration between them. Conversely, in events where transport problems were reported, one or more groups were often absent or poorly integrated. Traffic management has become a fundamental group present at all successful events. The creation of unified command centers (Beijing 2008, Rio 2016) has proven its importance for coordinating responses to changing conditions. The intelligent traffic management system in London in 2012 reduced the travel time of the audience by about 15-20%, demonstrating the tangible advantages of this group.

Information Systems for Users showed the most dramatic evolution over the study period. Early events relied on static information boards, while contemporary events utilize AI-powered mobile applications with personalized route recommendations. The 2022 Beijing Winter Games feedback system demonstrated how user input can be incorporated to improve services in real-time, reducing complaint rates by an estimated 30% compared to previous events. Road Safety services proved indispensable given the increased risk profiles during mass events. The integration of automatic incident detection with emergency service coordination reduced average response times by 40% in Beijing 2008 and established benchmarks for subsequent events.

Public Transport Management demonstrated particular importance for events with limited parking capacity. During the 2022 FIFA World Cup in Qatar, an integrated ticket sales system (tickets for matches combined with public transport passes) was introduced, which increased the share of public transport to 65%, which

significantly reduced traffic jams. During recent events, special attention has been paid to environmental safety services, and Paris 2024 has set new standards for the fleet of electric and hydrogen-powered vehicles. Real-time monitoring of emissions has enabled the development of dynamic routes to minimize environmental impacts in vulnerable areas.

Highly automated vehicles represent a new trend: autonomous transport highways will appear for the first time in Hangzhou 2022 and Beijing 2022. Although their scale is still limited, the number of human error-related incidents in the designated areas has decreased by 90%. Integration with other systems has become a crucial factor for all other groups. In cases where ITS was isolated from emergency services, urban infrastructure, or event management systems, coordination failures and service gaps occurred.

The study revealed significant differences in ITS requirements depending on the characteristics of the events:

- Large-scale events (the Olympic Games, the FIFA World Cup) require the full implementation of all seven groups due to their scale, duration, and international prominence.
- Major cultural events (festivals, concerts) benefit most from traffic management, information systems, and public transport management.
- Recurring events provide cumulative benefits by applying them multiple times, with each iteration improving based on previous data.

There are several limitations to this study that should be considered. First, access to detailed operational data varied from event to event, and more recent events provided more complete information. Secondly, the analysis mainly focused on successful events, which potentially underestimated the problems with implementation. Thirdly, the rapid development of technology means that the results obtained require constant updating.

Conclusion

In the context of changing geopolitical relations between different countries, holding mass events is becoming very important, contributing not only to cultural exchange, but also to the establishment of diplomatic relations, allowing people and entire countries to build new and maintain existing relations. In modern conditions of holding mass events, it is impossible without the use of intelligent transport system services, which become necessary to ensure effective traffic flow management and minimize negative consequences such as traffic congestion and traffic accidents.

This article analyzes and systematizes the experience of transport services for urban mass events, identifies the main ITS services necessary to ensure the effective provision of transport services: Traffic flow monitoring; Intersection management; Dedicated lanes; Access control of dedicated lanes, Informing road users, Parking zone management; Routing, Access control, Integrated tickets, Booking and trip planning system, Flexible management of the transport and logistics system, Control of pollutant emissions from vehicle traffic.

This article presents a comprehensive approach to managing the transport system during mass city events using intelligent transport systems service groups. By identifying seven key ITS service groups and proposing a conceptual ITS architecture, this study provides cities with a framework for preparing the transport system for mass city events. This approach is expected to reduce congestion, improve road safety, and improve user experience. The conceptual architecture contains practical recommendations for the implementation of the proposed solutions.

Future research should focus on testing simulation models for the implementation of the proposed architecture and real-world pilot studies to assess its effectiveness and adaptability in various environments. In addition, a thorough study of the possibilities of integrating highly automated vehicles, the use of artificial intelligence and the economic feasibility of the proposed infrastructure is required. To further expand the scope of organizing mass events, the developed ITS architecture should be tested by other researchers for practical implementation and further improvement.

Recommendations

Based on the findings of this study, the following recommendations are proposed for city administrators, event organizers, and transport planners preparing for mass events.

For City Administrators and Policymakers

Develop integrated ITS frameworks well in advance of scheduled events. The most successful implementations were planned three to five years before the event, allowing time for infrastructure development and system integration. Establish unified command centers that co-locate representatives from traffic management, emergency services, public transport, and event organization. Physical co-location proved essential for rapid decision-making in Beijing 2008, London 2012, and Rio 2016. Invest in scalable communication infrastructure capable of handling peak loads during events. Mobile applications and information systems must maintain functionality under high user demand, requiring cloud-based architecture with auto-scaling capabilities.

For Event Organizers

Conduct comprehensive modeling of transport demand before choosing venues and planning events. Agent-based simulation models that take into account audience behavior, transportation preferences, and time allocation can identify potential bottlenecks before they occur. Implement integrated ticketing systems that combine event access with public transportation privileges. This approach has made it possible to increase the use of public transport by 25-35 percent during successful events and reduce the demand for parking. Develop multi-channel communication strategies to ensure that transport information reaches all user groups through appropriate media. While mobile apps cater to a younger audience, dynamic information boards and announcements are still needed to ensure wider accessibility. Create feedback mechanisms that allow users to enter information in real time. The Beijing 2022 system has demonstrated that responding immediately to user concerns increases satisfaction and provides data for continuous optimization.

For Transport Planners and Engineers

Prioritize interoperability standards when selecting ITS components. Systems that cannot exchange data with existing urban infrastructure create integration challenges and reduce overall effectiveness. Design for legacy by ensuring that temporary event infrastructure integrates with long-term urban development plans. Many host cities, including Barcelona 1992 and London 2012, leveraged event investments to address pre-existing transport challenges. Implement adaptive traffic control systems capable of responding to changing conditions without manual intervention. Machine learning algorithms trained on historical event data can predict demand patterns and adjust signals proactively. Develop comprehensive testing protocols for all ITS components before event commencement. Simulation testing, phased rollouts, and pilot programs reduce the risk of failures during critical periods.

For Future Research

Validate the proposed architecture through simulation modeling and real-world pilot studies in diverse urban contexts. Quantitative assessment of effectiveness metrics would strengthen the evidence base. Investigate artificial intelligence applications for predictive transport management, particularly machine learning models trained on multi-event datasets. Conduct economic analysis of ITS investments for mass events, comparing implementation costs with measurable benefits including reduced congestion, improved safety, and enhanced user experience. Explore autonomous vehicle integration at scale, as current implementations remain limited to dedicated lanes and controlled environments. Research should address mixed traffic scenarios and regulatory frameworks. Develop standardized evaluation frameworks enabling comparative analysis across events and identification of best practices applicable to different event types and urban contexts.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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Author(s) Information

Olga Bulatova

Don State Technical University
1, Gagarin Square, 344003 Rostov-on-Don, Russia
ORCID iD: <https://orcid.org/0000-0003-1293-0937>

*Contact e-mail: mip.rnd@yandex.ru

Vladimir Zyryanov

Don State Technical University
1, Gagarin Square, 344003 Rostov-on-Don, Russia
ORCID iD: <https://orcid.org/0000-0002-5567-5457>

*Corresponding author(s) contact email

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Comparative Analysis of Conventional and Modern Control Techniques in PMSM Systems

Mahmut Furkan Oztok
Konya Technical University

Emre Hasan Dursun
Konya Technical University

Abstract: Permanent Magnet Synchronous Motors (PMSMs) are indispensable components of modern industrial systems, electric vehicles and renewable energy infrastructures due to their high efficiency, power density, wide speed range and superior torque to inertia ratio. However, maximizing the dynamic performance and energy efficiency of these machines requires advanced control strategies that offer robust stability against variable loads, parameter uncertainties and external disturbances. Furthermore, the inherent nonlinearities of PMSMs, such as magnetic saturation and cross-coupling effects, complicate the design of precise tracking controllers. To address this, this study provides a comprehensive theoretical review of both fundamental and contemporary control techniques for PMSMs. Conventional methods, including Scalar Control (V/f), Field-Oriented Control (FOC) and Direct Torque Control (DTC), are systematically classified alongside recent adaptive, intelligent and robust control approaches. These methodologies are comparatively evaluated based on critical performance criteria, including dynamic response, torque ripple mitigation, computational burden, implementation complexity and parameter sensitivity. By synthesizing these existing frameworks, this research establishes a solid theoretical foundation for future control strategy development, ultimately guiding researchers in designing high-performance, next-generation motor drive architectures.

Keywords: Permanent magnet synchronous motor, Control strategies, Robust and adaptive control

Introduction

Permanent Magnet Synchronous Motors (PMSMs) are widely preferred in a broad range of industrial applications, from low-power systems to high-power traction units, due to their high efficiency, superior torque-to-inertia ratio, and rapid dynamic response. Their robust structure and low maintenance requirements ensure reliable long-term performance, making them an ideal choice for robotics, electric vehicles, and wind energy conversion systems (Shneen et al., 2019). The critical role of PMSMs in modern industry is attributed not only to their electromechanical properties but also to the effectiveness of the control strategies implemented. Precise management of speed, torque, and current is essential to enhance energy efficiency and minimize oscillations under various operating conditions.

The non-linear nature of PMSMs and the complexities arising from the rotor-mounted permanent magnets necessitate advanced control methodologies beyond conventional techniques. Operational challenges such as unpredictable load variations and parameter uncertainties increase the demand for flexible and adaptive control systems (Hattab et al., 2024). Consequently, contemporary research focuses on managing the non-linear dynamics of the motor through diverse approaches. Methods such as Fuzzy Logic Control (FLC), vector control techniques like Field-Oriented Control (FOC), Adaptive Control, and Artificial Intelligence (AI) based techniques are prominent in the literature, each selected based on specific application requirements.

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Fuzzy Logic Control provides effectiveness in handling uncertain data and complex dynamics, ensuring stability under varying loads. Vector control, on the other hand, offers high precision by decoupling the magnetic flux and torque components. Adaptive control strategies allow the system to adjust parameters in real-time in response to environmental changes or system disturbances. Recently, computational intelligence approaches, including Artificial Neural Networks (ANN) and Reinforcement Learning (RL), have introduced new perspectives by enabling the control algorithms to learn and optimize motor behavior over time (Askour et al., 2024). Additionally, meta-heuristic optimization algorithms have proven highly effective in dynamically tuning controller parameters to handle non-linearities.

The optimization of PMSM control is vital not only for operational performance but also for energy sustainability. In electric vehicle applications, efficient control directly impacts driving range and minimizes energy losses. Similarly, in wind turbines, advanced control techniques facilitate more stable and efficient power generation. Innovations in PMSM control methodologies thus form the foundation for sustainable energy solutions and continue to be a strategic focus for both industrial and academic research.

Literature Review

The existing literature contains a multitude of studies focused on enhancing the operational robustness and performance metrics of PMSM control systems. Various methodologies have been proposed by researchers to tackle specific functional challenges, aiming to improve reliability, efficiency, and the integration of PMSMs into sophisticated technological sectors. For instance, a Fuzzy Logic Control (FLC) integrated Field-Oriented Control (FOC) approach was developed to autonomously adjust Proportional-Integral (PI) controller parameters in response to dynamic system fluctuations (Gu et al., 2019).

In another study, an FOC based sensorless intelligent speed regulation method was introduced to manage Inter-Turn Short Circuit (ITSC) faults by utilizing a Luenberger observer coupled with adaptive fuzzy logic (Kercha et al., 2023). Furthermore, the integration of neural networks with PI and fuzzy control strategies has been investigated to ensure robust performance in synchronous machines, emphasizing the necessity of rigorous performance analysis in hybrid architectures (Reddy et al., 2021). Additionally, the dynamic performance of sensorless PMSM control has been evaluated through hardware-in-the-loop tests using a Backstepping-PSO based controller supported by an Extended State Observer (ESO) (Nicola et al., 2021).

This paper offers an extensive evaluation of diverse control strategies, spanning from conventional methodologies to modern artificial intelligence-driven applications. The primary objective is to analyze sustainable and high-performance motor control technologies to facilitate innovative solutions for widespread PMSM implementation. The study is organized as follows: The subsequent section details the system configuration comprising the PMSM, control unit, and power unit—alongside a comparative analysis of control techniques. The concluding sections discuss performance parameters and provide recommendations for future research directions.

System Configuration

The general architecture and core components of the control system designed for PMSMs are presented in schematic form in Figure 1.

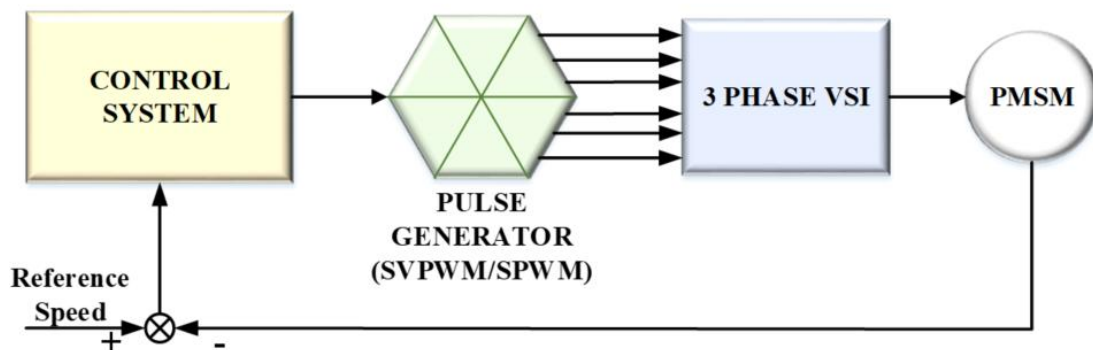


Figure 1. PMSM control system block diagram

The core framework of this system is primarily composed of a motor control unit, a PMSM, a Space Vector Pulse Width Modulation (SVPWM) module and three phase Voltage Source Inverter (VSI). This integrated architecture facilitates bidirectional power flow, ensuring both operational efficiency and high-precision control. In this operational scheme, a predefined reference speed is compared against the actual motor speed to derive an error signal.

Subsequently, the control system processes this error to generate specific command signals, which are then relayed to the SVPWM unit. As depicted in Figure 1, these commands are utilized to produce appropriate PWM switching pulses, which are then applied to the three-phase inverter to drive the PMSM. The control loop is closed through the continuous monitoring and feedback of speed and performance metrics. This closed-loop configuration maintains a steady interaction between the primary components, ensuring the accurate and high-performance operation of the PMSM.

PMSM

As depicted in Figure 2, the PMSM operates as a rotary electrical machine comprising a standard three-phase stator, akin to an induction motor (IM), yet it is distinguished by the integration of permanent magnets on its rotor. In contrast to IMs—which rely on induction and magnetizing currents to create the air-gap magnetic field—the PMSM generates this field directly utilizing its rotor magnets (Boztas, 2023). While the stator current in an IM must be divided between magnetization and torque generation components, the PMSM intrinsically sustains a steady air-gap flux via its permanent magnets. Consequently, the necessity for magnetizing current is entirely eliminated, allowing the stator current to be utilized exclusively for torque production. This distinct attribute enables the PMSM to achieve superior efficiency and a higher power factor when evaluated against an IM of comparable power capacity (Pillay & Krishnan, 1989; Aydogmus & Sunter, 2012).

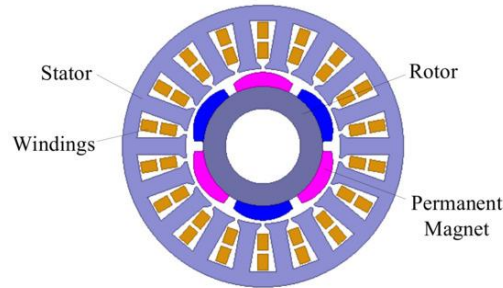


Figure 2. PMSM structure

Within a standard three-phase PMSM architecture, currents flowing through sinusoidally distributed stator windings produce a revolving magnetic field. Consequently, the rotor is compelled to synchronize with and track this generated flux vector. The generation of electromagnetic torque is governed by the load angle, which is defined as the phase discrepancy between the stator flux linkages and the rotor flux vector.

During the formulation of the mathematical model for the PMSM, specific foundational assumptions are adopted to streamline the analytical process. These preconditions entail the presumption of perfectly balanced stator windings and a strictly sinusoidal induced electromotive force (EMF), alongside the disregard of parameter fluctuations and magnetic saturation. Additionally, hysteresis and eddy current effects, collectively known as core losses, are omitted from the model. Implementing these reductions permits a concentrated investigation into the primary electromechanical behaviors of the machine (Puci et al., 2018). Accordingly, the stator voltage formulation within the stationary abc reference frame is given by the subsequent equation (Krause, 1986):

$$V_{abc} = R_s i_{abc} + \frac{d}{dt} \lambda_{abc} \quad (1)$$

In the established model, V_{abc} , i_{abc} , and λ_{abc} represent the stator phase voltages, stator phase currents, and flux linkages, respectively. Furthermore, to convert the control variables from the rotating $d-q$ reference frame back to the stationary $a-b-c$ frame, the Inverse Park Transformation is utilized. For instance, the transformation for the c -phase component is formulated in Equation 2 (Şerifoğlu, 2007).

$$F_c = F_d \cos(\theta + \frac{2\pi}{3}) - F_q \sin(\theta + \frac{2\pi}{3}) \quad (2)$$

where F_c represents the physical variable in the stationary c -phase; F_d and F_q denote the corresponding components in the rotating d -axis and q -axis, respectively; and θ is the electrical rotor position. The term $2\pi/3$ accounts for the 120° spatial displacement of the c -phase. This coordinate transformation is essential for generating the actual physical signals required to drive the PMSM.

The implementation of the $dq0$ transformation within the rotor reference frame enables the motor equations to be expressed in a simplified and decoupled structure. This transformation is fundamental for linearizing the complex dynamics of the motor and supporting sophisticated regulation architectures. As illustrated in Figure 3, these mathematical relationships can be represented through the d and q axis equivalent circuit diagrams which clarify the interaction between stator voltages and magnetic flux components. These simplified analytical models are defined by the subsequent equations (Chapman, 2007).

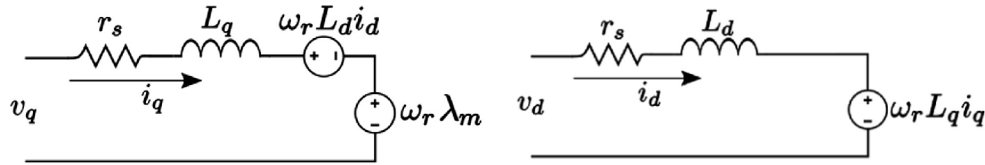


Figure 3. PMSM circuit diagram (Chapman, 2007).

$$v_{qs}^r = R_s i_{qs}^r + \omega_{re} \lambda_{ds}^s + \frac{d\lambda_{qs}^s}{dt} \quad (3)$$

$$v_{ds}^r = R_s i_{ds}^r - \omega_{re} \lambda_{qs}^s + \frac{d\lambda_{ds}^s}{dt} \quad (4)$$

$$\lambda_{qs}^s = L_{qs} i_{qs}^r \quad (5)$$

$$\lambda_{ds}^s = L_{ds} i_{ds}^r + \lambda_f \quad (6)$$

$$T_e = \frac{3P}{4} (\lambda_{fs}^r i_{qs}^s - \lambda_{qs}^r i_{ds}^s) \quad (7)$$

In the provided formulations, Equations 3 and 4 define the stator voltage components along the q and d axis respectively. Similarly, Equations 5 and 6 describe the flux linkages for the dq axes. Finally, the electromagnetic torque is formulated in Equation 7. The three-phase stator voltages of the motor utilized in this study are expressed through Equations 8, 9 and 10 (Leonard & Murphy, 2001).

$$V_{as} = V_m \sin(\omega t) \quad (8)$$

$$V_{bs} = V_m \sin(\omega t - \frac{2\pi}{3}) \quad (9)$$

$$V_{cs} = V_m \sin(\omega t + \frac{2\pi}{3}) \quad (10)$$

Within these mathematical representations V_{as} , V_{bs} , and V_{cs} indicate the phase voltages of the stator for phases A, B and C. Furthermore, V_m , stands for the maximum amplitude of the stator voltage. The inherent nonlinearity in the dynamics of PMSMs makes their regulation highly challenging. While traditional linear techniques such as Proportional Integral regulators remain popular due to their straightforward architecture, they frequently fall short of delivering optimal results during demanding operational scenarios. Such conventional controllers cannot adequately manage the nonlinear characteristics of these motors. This inadequacy leads to restricted operational efficiency and compromised stability under fluctuating conditions (Xiao et al., 2022).

Escalating demands from the industrial sector have exposed the insufficiencies of linear regulation algorithms when subjected to the severe working environments typical of PMSMs. Contemporary applications strictly require sophisticated methodologies that can sustain excellent operational standards despite fluctuating payloads and outside interferences. Numerous academic studies have concentrated on designing novel regulation architectures to bypass these obstacles (Zhang & Tang, 2021). Scholars have successfully improved system resilience and regulation effectiveness across a wide range of working states by incorporating nonlinear frameworks, adaptive mechanisms and smart computational algorithms. These improvements have allowed PMSMs to meet the rigorous criteria of modern commercial and manufacturing applications (Ye, 2019). As a result, a wide array of regulation paradigms has emerged to satisfy these continuously growing necessities.

PMSM Control

PMSMs are extensively utilized in low- to medium-power applications and are preferred in high-performance electric drive systems such as electric vehicles, robotics, aerospace, and machine tools (Ma & Li, 2020). However, the nonlinear nature of motor models and the uncertainties encountered in speed control systems during operation make it difficult for conventional PI control topologies to meet high performance requirements. Consequently, contemporary research focuses heavily on mitigating these uncertainties and enhancing system robustness (Zheng et al., 2021).

Since the introduction of speed regulation for AC motors, vector control methods have gained significant popularity with Direct Torque Control (DTC) and Field-Oriented Control (FOC) being the most prevalent. FOC is widely adopted in PMSM applications due to its ability to provide rapid and precise decoupling of torque and flux. Typically, PI controllers are integrated into FOC structures for current and speed regulation due to their simple design. However, since PI gains are generally determined based on nominal motor parameters, stability cannot be guaranteed in the presence of load variations, parameter uncertainties, or input saturation. Therefore, these controllers may be inadequate for applications requiring extreme precision and high dynamic performance (Ullah et al., 2022).

To address these limitations, several advanced nonlinear control topologies have been developed. These include Artificial Neural Network (ANN) control, Backstepping Control, Active Disturbance Rejection Control (ADRC), Fuzzy Logic Control (FLC), Model Predictive Control (MPC), Sliding Mode Control (SMC), Adaptive Control and various observer-based techniques such as Extended State Observers (ESO). Additionally, H_∞ control is utilized as an alternative to traditional PI methods for speed regulation, where external disturbances are treated as uncertain parameters with bounded energy. Many of these robust strategies, including mixed sensitivity-based controllers, have been successfully implemented in practical PMSM systems to enhance speed regulation (Yang et al., 2021).

H_∞ Robust Control

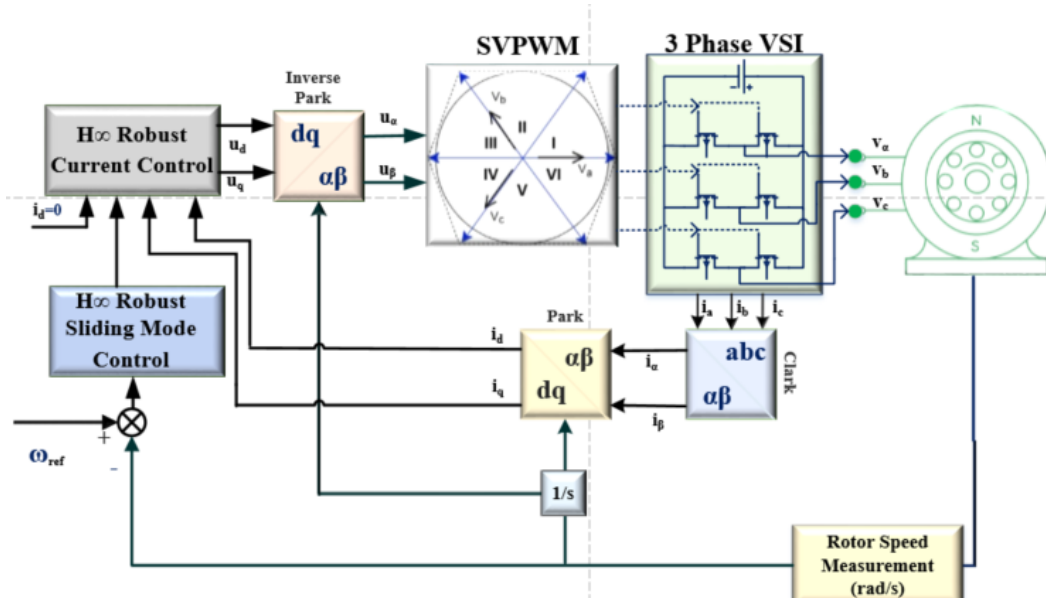


Figure 4. SMC-based H_∞ robust control block diagram for PMSM

H_∞ robust control is an advanced methodology designed to enhance system resilience against parameter uncertainties and external disturbances. The primary objective of this approach is to minimize the H_∞ norm of the system, which represents the maximum input-output gain under worst-case scenarios. Reducing this norm ensures that the system remains robust against external disturbance signals. This control strategy facilitates designs that account for modeling errors and uncertainties, offering a significant advantage by guaranteeing system stability and maintaining optimal performance in the presence of model-plant mismatches (Green & Limebeer, 2012). The H_∞ control method is widely applied across various domains, ranging from energy systems to automation and motor control. Specifically, in PMSM control, it provides an effective solution for mitigating disturbance effects in high-precision applications such as speed and position control (Saber et al., 2007). The method is extensively utilized to ensure robust stability in nonlinear systems and enhance dynamic performance against external perturbations. The block diagram of an H_∞ control system based on Sliding Mode Control (SMC) for a PMSM is illustrated in Figure 4.

Predictive Current Control (PCC)

Predictive Current Control (PCC) serves as a specialized regulation strategy for PMSMs aimed at streamlining the system framework and enhancing immunity against parameter fluctuations. This methodology utilizes a predictive model and a cost function to optimize the current control process which significantly boosts the dynamic performance of the motor. The strategy effectively neutralizes the negative impacts caused by deviations in inductance parameters within the regulation system. While some observer-based approaches aim to mitigate disturbances, they frequently introduce excessive design complexity and can potentially compromise the overall equilibrium of the system. To resolve these issues, recent academic investigations have introduced innovative PCC structures. A basic representation of this predictive control framework, comprising a cost function, model prediction and delay compensation units, is displayed in Figure 5 (Kuz'Menko, 2020).

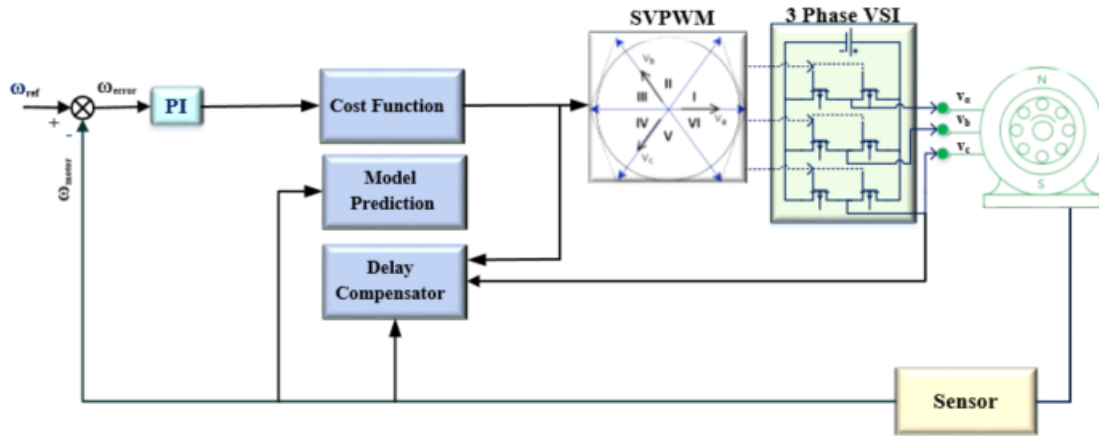


Figure 5. PCC block diagram for PMSM

Proportional Integral (PI) Control

PI controllers represent a conventional control strategy widely utilized across various industrial automation and drive applications. These controllers consist of a proportional gain and an integral action, which are collectively responsible for accelerating the control response, minimizing steady-state errors, and ensuring the system reaches a stable equilibrium. The input to the PI controller is defined as the error signal, representing the difference between the reference speed and the actual measured speed. The mathematical relationship between the input error and the controller output is expressed in Equation 11.

$$u(t) = K_p e(t) + K_i \int e(t) dt \quad (11)$$

where $u(t)$ is the control output signal and the speed error is defined as $e(t) = \omega_{ref} - \omega$. The performance of the PI controller is strictly dependent on the proper tuning of proportional K_p and integral K_i gains. However, a PI controller designed based on specific model parameters and time-discretization assumptions cannot guarantee stability in the presence of uncertainties, load variations, or input saturation limits. In PMSM control, when a significant set-point change occurs, the PI controller utilizes its integral action to mitigate the cumulative error.

The fundamental operational block diagram of a conventional PI speed control loop for a PMSM is illustrated in Figure 6 (Kung et al., 2015).

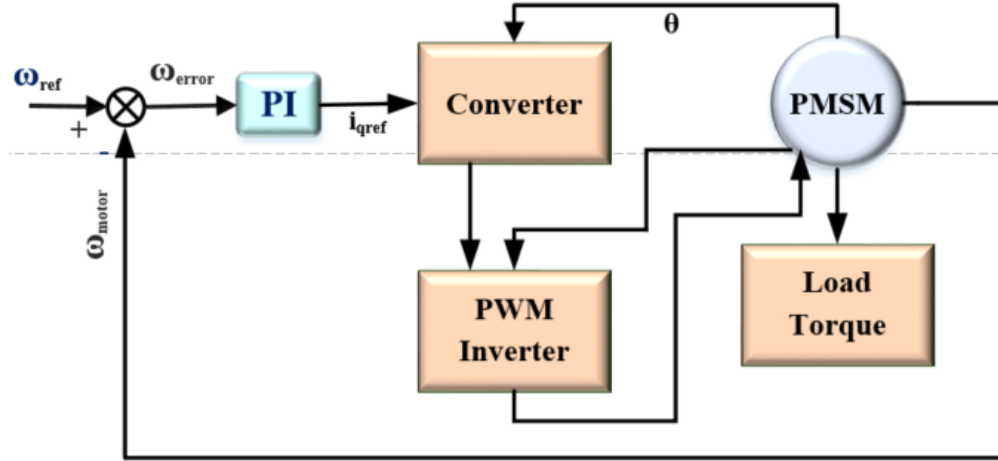


Figure 6. PI control block diagram for PMSM

Sliding Mode Control (SMC)

Sliding Mode Control (SMC) is a robust speed regulation methodology widely adopted for PMSM applications. It has been extensively investigated in literature and implemented across various systems through diverse approaches. As a nonlinear control technique, SMC exhibits remarkable insensitivity to motor parameter variations and load disturbances. The method employs a switching algorithm to ensure that the system state trajectories track a predefined path on the phase plane, known as the sliding surface (Lu et al., 2021).

However, SMC is inherently limited by high-frequency oscillations, termed "chattering," which arise from the switching function once the sliding mode is reached. This phenomenon presents a significant challenge in high-precision applications such as industrial robotics and machine tools. To mitigate this issue, advanced methodologies, including reaching law-based SMC, fractional-order sliding mode control, and boundary layer methods, have been developed. While these approaches reduce chattering intensity, they often fail to eliminate it completely in the presence of external disturbances. Consequently, integrating disturbance observers to optimize SMC performance and provide disturbance compensation has become a primary research focus. The structural schematic of an observer-based SMC is illustrated in Figure 7 (Ullah et al., 2022).

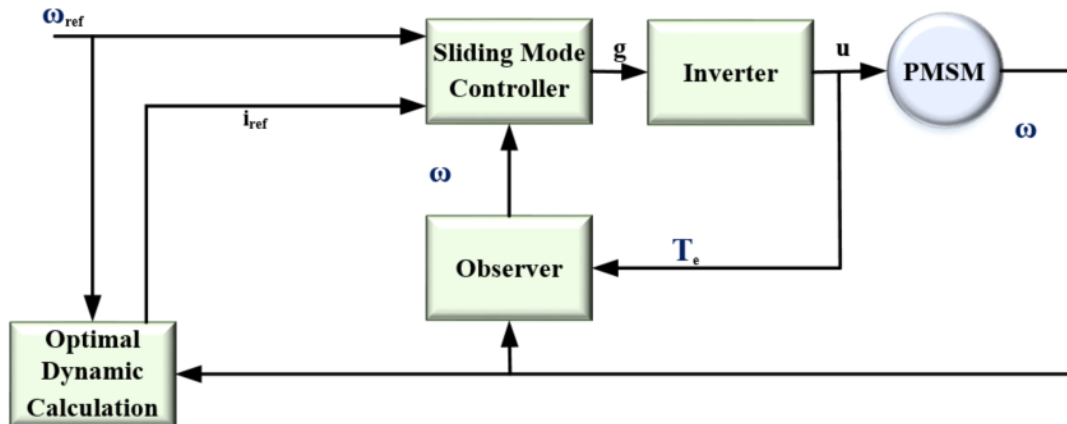


Figure 7. An observer-based SMC block diagram for PMSM

Fuzzy Logic Control (FLC)

Fuzzy logic regulation functions as a controller governed by rules that employ algorithms based on linguistic tactics. This method successfully integrates human proficiency into the regulation framework without the necessity of exact mathematical formulations. These linguistic tactics mimic the cognitive choices of humans

through the application of fuzzy logic principles extracted from specialist insight. As a result, this mechanism proficiently governs intricate nonlinear structures even when strict mathematical descriptions are unavailable.

Converting specialist insight into conditional statements allows the system to evaluate ambiguous signals and offers a highly adaptable methodology for operational regulation. The initial fuzzification stage translates precise inputs like velocity deviations into fuzzy domains. Following this, the knowledge foundation enforces logical conditions on these domains and the final defuzzification phase reverts these outputs into definite figures for actual execution within the hardware. Such a structural design empowers the methodology to supply dependable execution across diverse fields including manufacturing automation and commercial gadgets where standard approaches frequently fail (Hattab et al., 2024). The primary elements of this architecture are illustrated in Figure 8 whereas the design for PMSM regulation driven by fuzzy logic is depicted in Figure 9.



Figure 8. FLC General Working Scheme

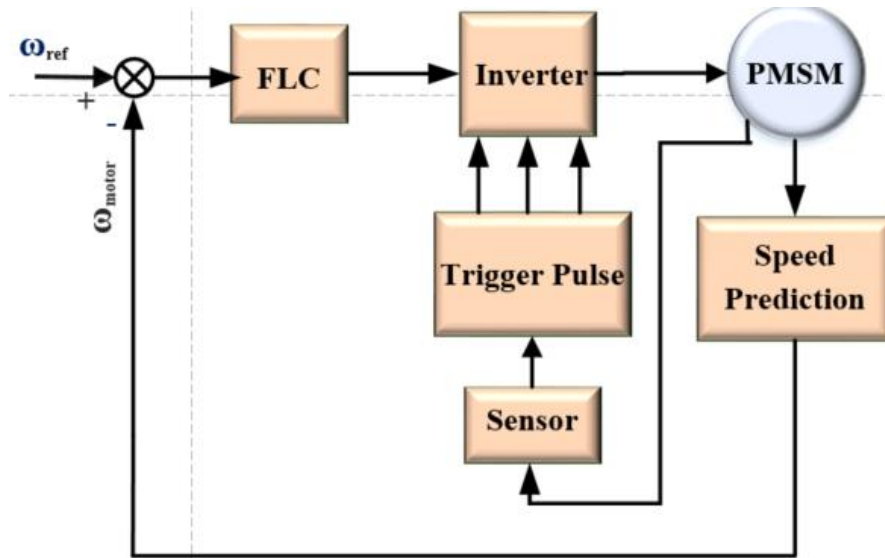


Figure 9. FLC block diagram for PMSM

Artificial Neural Network (ANN)-Based Control

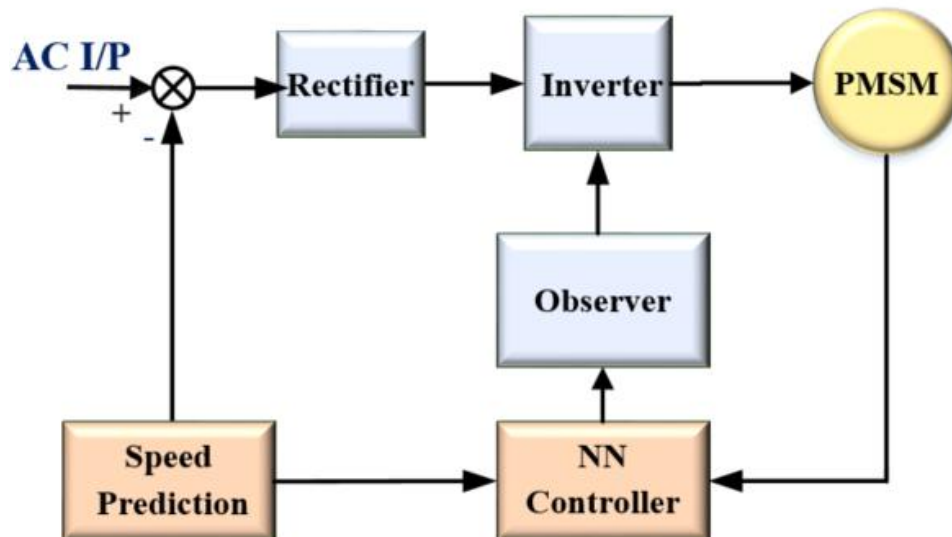


Figure 10. ANN-based control block diagram for PMSM

ANN-based control is a learning-oriented approach that can be implemented for speed, position, or current regulation in PMSMs. By modeling the nonlinear dynamics of the motor, ANNs learn and predict complex system behaviors. This methodology is particularly preferred for providing control under parameter uncertainties or varying operating conditions. Compared to conventional control methods, ANNs optimize system performance through their offline learning capabilities and online adaptation features. In PMSM control, ANNs are generally utilized for the adaptation of PI controller gains or for providing direct speed and torque control. Consequently, energy efficiency is increased, and system stability is significantly improved (Ghamri et al., 2019). A general block diagram of a PMSM control system regulated by an ANN is illustrated in Figure 10.

Field Oriented Control (FOC)

Field oriented control is broadly acknowledged as a remarkably efficient and dependable methodology for governing permanent magnet synchronous motor operations. Throughout the previous twenty years, swift progress within power electronics, processing capacities and microelectronics has promoted the widespread adoption of vector regulation mechanisms within superior alternating current applications. This methodology permits accurate regulation by separating magnetic flux and rotational force elements, like the functioning attributes of an independently stimulated direct current machine (Öztok & Dursun, 2025).

The technique utilizes current regulation circuits engineered to manage electrical flows across the d and q axis individually. A standard diagram representing this framework, which includes an external velocity circuit and separate internal current loops to attain maximum efficiency in these motor structures, is presented in Figure 11. Inside these sequential circuits, standard proportional integral mechanisms are customarily utilized for velocity and flow management, guaranteeing the productive and steady functioning of the driving machinery (Petkar&Kumar,2020).

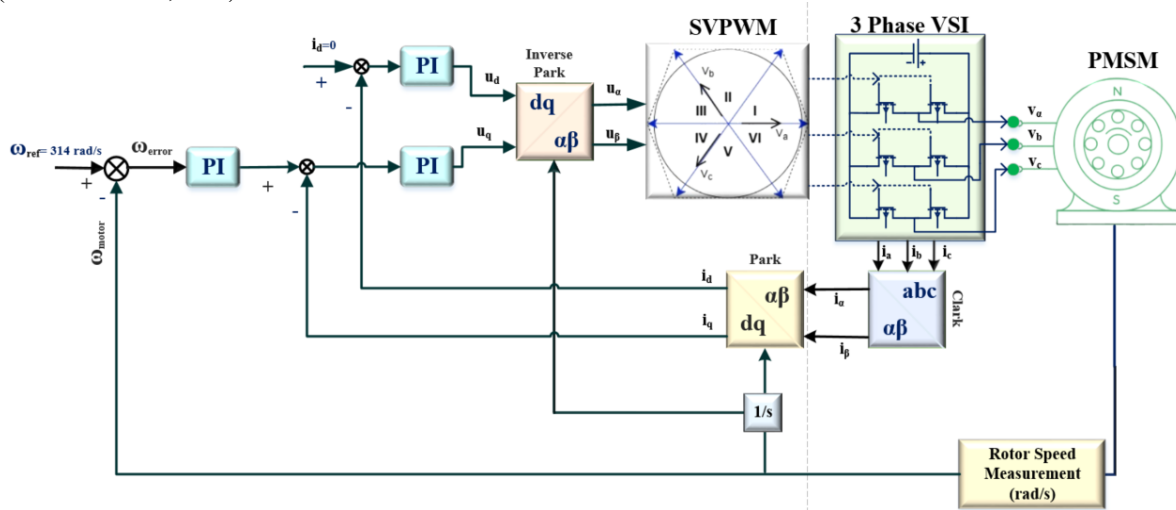


Figure 11. FOC block diagram for PMSM

Comparative Analysis and Discussion

Table 1. Comparison of control techniques

Control Technique	Advantages	Disadvantages
PI Control	Simple implementation; Low computational cost.	Poor performance under load variations; Sensitivity to parameter changes.
FOC	High precision in torque/flux; Excellent dynamic response.	Requires accurate rotor position; Dependent on motor parameters.
SMC	High robustness against disturbances; Insensitivity to parameter mismatch.	Chattering phenomenon; Complex switching algorithm.
FLC/ANN	No precise mathematical model required; Handles nonlinearities effectively.	High computational demand; Rule/training data dependency.
PCC/ H_∞	Predicts future states; Superior disturbance rejection.	Sensitive to model inaccuracies; Complex mathematical derivation.

A comparative analysis of the discussed control strategies reveals that each methodology possesses specific strengths and limitations depending on the application requirements. As illustrated throughout this review, the selection of an appropriate control strategy is a critical determinant of PMSM drive performance. The findings regarding the operational advantages and inherent drawbacks of these techniques are synthesized in Table 1.

Conclusion

This study has provided a comprehensive theoretical review of various control methodologies for PMSMs, ranging from conventional PI and FOC to advanced nonlinear and intelligent techniques. Analysis indicates that while traditional methods are sufficient for standard applications, high-performance systems require robust and adaptive strategies to mitigate the effects of nonlinearities and external disturbances.

Future research will focus on the simulation and real-time experimental validation of these control techniques. Specifically, the development of hybrid control architectures integrated with metaheuristic optimization algorithms—such as the Whale Optimization Algorithm (WOA) or Particle Swarm Optimization (PSO)—is planned to achieve an optimal balance between dynamic response and steady-state accuracy. These hybrid approaches aim to optimize control parameters autonomously, paving the way for next-generation, self-adaptive PMSM drive systems.

Recommendations

To overcome the inherent limitations of individual control strategies, it is recommended to develop hybrid architectures that combine Sliding Mode Control (SMC) with Fuzzy Logic or ANN to eliminate chattering phenomenon while maintaining system robustness. Furthermore, future studies should prioritize real-time experimental validation using high-speed Digital Signal Processors (DSPs) to assess the computational feasibility of these complex algorithms. Additionally, the integration of meta-heuristic optimization for continuous, autonomous parameter tuning is strongly suggested to enhance system adaptability under dynamic load variations. Ultimately, these advancements are essential for developing next-generation, self-optimizing PMSM drive systems.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest (If the number of authors is more than one)

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Author(s) Information

Mahmut Furkan Oztok

Konya Technical University

Selçuklu/Konya, Türkiye

ORCID iD: <https://orcid.org/0000-0002-3179-8540>

*Contact e-mail: mfoztok@ktun.edu.tr

Emre Hasan Dursun

Konya Technical University

Selçuklu/Konya, Türkiye

ORCID iD: <https://orcid.org/0000-0001-9286-0195>

*Corresponding author(s) contact email

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Pilot-Scale Laboratory Equipment for Agitated Gold Cyanidation

Nikolay Nestorov

University of Mining and Geology “St. Ivan Rilski”

Irena Grigorova

University of Mining and Geology “St. Ivan Rilski”

Abstract: Gold cyanidation remains the dominant hydrometallurgical technology for gold extraction, accounting for more than 78% of global production, despite persistent environmental and process-efficiency challenges. Although cyanidation chemistry is well established, a critical gap persists in the availability of pilot-scale laboratory systems capable of ensuring precise hydrodynamic control, regulated aeration, automated reagent dosing, and long-term operational stability required for reliable kinetic evaluation. This study presents the design, construction, and validation of a pilot-scale laboratory installation for agitated cyanidation of gold-bearing ores, concentrates, and tailings. The system integrates chemically resistant reactor materials, optimized propeller-driven mixing, controlled air dispersion, automated peristaltic reagent dosing, and vacuum-assisted sampling for continuous monitoring. A structured experimental program was conducted to determine optimal cyanide dosage, aeration rate, pulp density, pH control strategy, and leaching duration under stabilized process conditions. The installation enables continuous operation for up to 168 hours, multi-sample parallel testing, and minimal operator intervention while maintaining high reproducibility and operational stability. The results demonstrate that the system provides a robust experimental framework for kinetic evaluation and reagent optimization. The proposed configuration bridges the methodological gap between conventional laboratory testing and industrial cyanidation circuits, offering a scalable platform for advanced hydrometallurgical research.

Keywords: Gold, Cyanidation, Hydrometallurgy, Laboratory equipment, Process optimization

Introduction

The sustained expansion of advanced technologies has led to a continuous increase in global gold demand, reinforcing its strategic importance in electronics, aerospace systems, catalysis, green energy technologies, and high-precision manufacturing. This growing technological dependence necessitates the development of efficient, reliable, and economically sustainable gold extraction processes. In primary gold-bearing ores, gold predominantly occurs as native gold (Au) and electrum (Au, Ag), and less frequently as gold and gold-silver tellurides. Depending on mineralogical characteristics, beneficiation strategies typically involve gravity concentration, flotation, cyanidation, or integrated flowsheets combining these methods (Badri & Zamankhan, 2013; Li et al., 2023).

For more than 130 years, cyanidation - known as the MacArthur-Forrest process has remained the dominant industrial technology for gold extraction, accounting for over 78% of global production (Egan et al., 2016; Oraby et al., 2020; Shi, 2024). The process is based on the oxidative dissolution of metallic gold in dilute alkaline cyanide solutions, forming stable aurocyanide complexes. Owing to its selectivity, cost-efficiency, and adaptability to low-grade materials, cyanidation continues to be the principal hydrometallurgical method for gold recovery (Hilson & Monhemius, 2006; Liu et al., 2022).

Low-grade and refractory ores represent more than 30% of global gold reserves and constitute a significant economic resource (Li et al., 2023). In such materials, gold is frequently encapsulated within sulfide minerals

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such as pyrite, arsenopyrite, and chalcopyrite or occurs as submicroscopic inclusions (“invisible gold”), which significantly hinder direct leaching (Benzaazoua et al., 2007; Chen et al., 2018). Consequently, direct cyanidation of refractory ores often results in low recoveries unless preceded by oxidative pretreatment processes, including roasting, pressure oxidation, or bioleaching, aimed at liberating encapsulated gold particles (Qin et al., 2021; Lin et al., 2022).

The performance of cyanide leaching is governed by a complex interplay of mineralogical, chemical, and hydrodynamic factors. Key operational parameters include particle size distribution, cyanide concentration, dissolved oxygen availability, pulp density, pH, agitation intensity, and leaching duration (Egan et al., 2016; Han et al., 2024; Shi, 2024). Optimization of these variables through controlled experimentation and statistical modeling has been shown to significantly improve gold recovery; for example, Azizi and Ghaedrahmati (2015) achieved 91.5% gold recovery under optimized operational conditions.

Despite its technological maturity, cyanidation poses significant environmental and safety challenges due to the inherent toxicity of cyanide. Maintaining alkaline conditions ($\text{pH} > 10.5$) is essential to prevent the formation of hydrogen cyanide (HCN) gas and to ensure process stability (Marsden & House, 2006). Although substantial research has been directed toward alternative lixiviants, including thiosulfate- and glycine-based systems, most alternatives remain at experimental or pilot scale and have not achieved large-scale industrial implementation (Hilson & Monhemius, 2006; Gökelma et al., 2016; Zhang et al., 2022; Wu et al., 2022; Liu et al., 2022).

While the chemistry and operational variables of cyanidation are extensively documented, comparatively limited attention has been directed toward the engineering design and experimental validation of pilot-scale laboratory systems that integrate controlled hydrodynamics, regulated aeration geometry, automated reagent dosing, and long-term operational stability within a single experimental platform. The absence of such integrated systems may restrict the reliability of kinetic modeling and hinder the accurate transfer of laboratory findings to industrial-scale cyanidation circuits.

Accordingly, the present study goes beyond conventional laboratory testing by developing and experimentally validating a pilot-scale cyanidation installation specifically designed to ensure reproducible hydrodynamic conditions, controlled chemical stability, and extended operational performance. The proposed configuration provides a methodological contribution to experimental hydrometallurgy by bridging the gap between small-scale batch testing and industrial process simulation.

Materials and Methods

Design and Construction of the Pilot-Scale Cyanidation System

The pilot-scale laboratory installation for agitated gold cyanidation was designed as an integrated mechanical and process-control platform comprising structural housing, reaction vessels, propeller-type impellers, independent electric drives with inverter regulation, aeration modules, and automated reagent dosing systems. The overall configuration of the unit is presented in Figure 1.



Figure 1. Laboratory equipment

Structural Housing

The main frame of the installation was fabricated from 18 mm hydrophobic multilayer plywood selected for its mechanical strength, abrasion resistance, dimensional stability, and moisture tolerance under prolonged laboratory operation. The system incorporates five independent working stations separated by protective partitions to ensure operational safety and experimental isolation. Each station is equipped with an individual electric motor, enabling independent adjustment of agitation parameters and simultaneous multi-sample testing under controlled conditions.

Reaction Vessels and Agitation System

The reaction vessels were manufactured from polycarbonate (PC), a high-performance transparent polymer characterized by elevated mechanical strength, chemical resistance, thermal stability, and fire-retardant properties. Material selection ensures long-term compatibility with alkaline cyanide media. To provide experimental flexibility for materials of varying gold grades, two reactor volumes were implemented:

- 3000 ml vessels for low-grade ores and tailings,
- 1500 ml vessels for high-grade concentrates.

All vessels are cylindrical and equipped with dual-layer lids incorporating dedicated ports for impeller shafts, reagent addition, aeration, and slurry sampling, enabling closed-system operation with full process accessibility.

Pulp homogenization is achieved through propeller-type impeller assemblies designed to generate intensive hydrodynamic mixing and maintain a fully homogeneous suspension of solid particles. The configuration prevents sedimentation of dense mineral fractions and promotes uniform mass transfer conditions throughout the reactor volume. Reversible rotation capability allows additional control of flow patterns and suppression of vortex formation.

The impellers were fabricated from austenitic stainless steel AISI 316, selected for its mechanical robustness and corrosion resistance under strongly alkaline cyanide conditions. Rotational speed is regulated via inverter-controlled motor drives, permitting precise adjustment of agitation intensity in accordance with hydrodynamic and kinetic requirements.

Aeration System

Aeration was achieved by introducing compressed atmospheric air into the reaction vessels to ensure sufficient dissolved oxygen for the oxidative dissolution of gold. When a specific gaseous environment is required, oxygen or nitrogen may be used instead of air. A series of preliminary trials was conducted to determine the optimal air-injection geometry. The most effective configuration was identified at the vessel periphery, positioned 10 mm below the lower dead center of the impeller. This arrangement enhanced oxygen dispersion, improved gas-liquid mass transfer, and stabilized hydrodynamic conditions without excessive turbulence. Airflow rates were controlled using calibrated glass aerometers (0.1-6 L/min), enabling precise regulation of oxygen supply throughout the leaching process.

Reagent Addition and Process Control

Reagents in aqueous form, including sodium cyanide (NaCN) and pH modifiers, were introduced via peristaltic metering pumps to maintain controlled chemical conditions during leaching. The system supports integration with microprocessor-based control for automated regulation of cyanide concentration and alkalinity. This dosing strategy reduces fluctuations in reagent levels, enhances experimental reproducibility, and minimizes excess reagent consumption. Manual reagent addition via calibrated syringes was retained for short-duration or corrective adjustments.

Slurry Sampling and Monitoring

Slurry samples were collected using disposable tubes (10 ml and 25 ml) connected to a silicone probe integrated into a vacuum-assisted extraction system. This configuration enables representative sampling with minimal disturbance to reactor hydrodynamics. The sampling protocol allows automated periodic collection during long-term experiments of up to 168 hours, supporting continuous process monitoring and reliable kinetic evaluation while limiting operator intervention.

Determination of Gold Recovery and Reagent Consumption

After establishing the optimal grinding fineness of the feed material, a structured experimental program was conducted to determine optimal reagent consumption, including NaCN dosage and pH adjustment requirements. Controlled variation of reagent input allowed identification of concentration ranges that maximize gold dissolution efficiency while limiting unnecessary consumption. Time-dependent leaching experiments were subsequently performed to determine the cyanidation duration corresponding to maximum gold recovery under stabilized chemical and hydrodynamic conditions.

Dissolved gold concentrations were determined by inductively coupled plasma (ICP) analysis following microwave-assisted digestion. Residual gold in solid phases was quantified using fire assay and flame atomic absorption spectrometry in accordance with BDS ISO 10378:2018. The combined analytical approach ensures accurate mass balance evaluation and reliable calculation of gold recovery.

Experimental Conditions

All cyanidation experiments were conducted under controlled laboratory conditions using the pilot-scale installation described above. The feed material was crushed to a particle size below 1.7 mm prior to grinding. The ore was subsequently ground to target fineness levels of $P_{60} = 75 \mu\text{m}$ (i.e., 60% passing $75 \mu\text{m}$) and $P_{80} = 75 \mu\text{m}$ for the two experimental series.

Leaching tests were performed at a solids concentration of 40%, using an initial solid mass of 1000 g and a pulp volume of 1500 ml. Agitation was maintained continuously throughout the experiments, and aeration was provided at a controlled airflow rate of 3.0 L/min. The pH of the pulp was maintained above 10.5 to ensure cyanide stability and safe operating conditions.

The total duration of each cyanidation experiment was 48 hours. Incremental additions of sodium cyanide (NaCN) were applied according to the predetermined dosing schedule, resulting in total cyanide consumptions of 2.98 g for the $P_{60} = 75 \mu\text{m}$ test and 2.95 g for the $P_{80} = 75 \mu\text{m}$ test. Lime addition remained constant at 0.37 g in all experiments. Additions of sodium cyanide (NaCN) were applied as needed to maintain its concentration during leaching, resulting in total cyanide consumptions of 2.98 g for the $P_{60} = 75 \mu\text{m}$ test and 2.95 g for the $P_{80} = 75 \mu\text{m}$ test. Sampling was conducted at predefined time intervals using 25 mL slurry aliquots to monitor free cyanide concentration and dissolved gold content.

Results and Discussion

Two experimental series were conducted to evaluate the kinetics of agitated cyanide leaching of the investigated copper-porphyry gold-bearing ore at two grinding fineness levels: $P_{60} = 75 \mu\text{m}$ and $P_{80} = 75 \mu\text{m}$. The controlled operational parameters, including solids concentration, aeration rate, particle size distribution, and total leaching time, are summarized in Table 1. By maintaining identical process conditions, particle size distribution was effectively isolated as the primary variable influencing gold recovery.

Table 1. Leach test conditions

Parameters	$P_{60} = 75 \mu\text{m}$	$P_{80} = 75 \mu\text{m}$
Solids, %	40.0	40.0
Pretreatment	Crushing	Crushing
Crush size, mm	<1.7	<1.7
Leaching time, h	48	48
Air rate, L/min	3.0	3.0
Sample volume, ml	25	25

The cumulative reagent additions applied during the experiments are detailed in Table 2. Total sodium cyanide consumption reached 2.98 g for the $P_{60} = 75 \mu\text{m}$ test and 2.95 g for the $P_{80} = 75 \mu\text{m}$ test, while lime addition remained constant at 0.37 g in both cases. These data indicate comparable cyanide demand under both grinding regimes, despite the differences in recovery behavior.

Table 2. Leach test additions

Leaching time (hr)	$P_{60} = 75 \mu\text{m}$				$P_{80} = 75 \mu\text{m}$			
	Solids (g)	Solution (ml)	NaCN (g)	Lime (g)	Solids (g)	Solution (ml)	NaCN (g)	Lime (g)
0	1000	1500	1.50	0.37	1000	1500	1.50	0.37
2	0	1490	0.27	0.00	0	1490	0.25	0.00
4	0	1500	0.30	0.00	0	1490	0.25	0.00
6	0	1490	0.30	0.00	0	1500	0.33	0.00
24	0	1450	0.45	0.00	0	1450	0.46	0.00
30	0	1480	0.16	0.00	0	1480	0.16	0.00
48	0	1440	0.00	0.00	0	1440	0.00	0.00
total	1000	1500	2.98	0.37	1000	1500	2.95	0.37

The evolution of pH, free cyanide concentration, and dissolved gold content throughout the leaching process is presented in Table 3. The pH remained consistently above 10.5, in accordance with established operational practice, thereby ensuring stable alkaline conditions and preventing the evolution of HCN gas (Marsden & House, 2006). The stability of the alkaline environment maintained cyanide in its stable ionic form and minimized reagent loss.

Table 3. Leach test results (solution data)

Leaching time (hr)	$P_{60} = 75 \mu\text{m}$			$P_{80} = 75 \mu\text{m}$		
	pH	NaCN (%)	Au (ppm)	pH	NaCN (%)	Au (ppm)
0	10.92	0.100	-	10.92	0.100	-
2	10.90	0.075	0.407	10.90	0.082	0.342
4	10.90	0.128	0.514	10.90	0.119	0.432
6	10.91	0.123	0.560	10.88	0.116	0.482
24	10.88	0.062	0.651	10.88	0.062	0.623
30	10.85	0.086	0.666	10.88	0.076	0.610
48	10.83	0.050	0.657	10.85	0.046	0.616
total	10.88	0.089	-	10.89	0.086	-

Leaching Kinetics and Cyanide Availability

The time-dependent dissolution behavior of gold, calculated from solution analyses, is summarized in Table 4 and further quantified in terms of cumulative recovery in Table 5. Gold recovery values were calculated based on mass balance between dissolved and residual gold concentrations determined by ICP and fire assay analysis. The results demonstrate a pronounced initial dissolution phase during the first 6 hours, followed by a progressive deceleration and approach toward a kinetic plateau.

Table 4. Leach test results (sample data)

Leaching time (hr)	$P_{60} = 75 \mu\text{m}$				$P_{80} = 75 \mu\text{m}$			
	Volume (ml)	Free CN (mg/L)	Au (μg)	Σ Au (μg)	Volume (ml)	Free CN (mg/L)	Au (μg)	Σ Au (μg)
0	-	540	-	-	-	540	-	-
2	25	405	10.18	10.18	25	445	8.55	8.55
4	25	690	12.85	23.03	25	645	10.80	19.35
6	25	665	14.00	37.03	25	625	12.05	31.40
24	25	335	16.28	53.30	25	335	15.58	46.98
30	25	465	16.65	69.95	25	410	15.25	62.23
48	25	270	16.43	86.38	25	250	15.40	77.63
total	150	481	-	-	150	464	-	-

Maximum gold recovery was achieved after 30 hours of leaching for both grinding conditions, as shown in Table 5. The $P_{60} = 75 \mu\text{m}$ sample reached 75.84% recovery, whereas the $P_{80} = 75 \mu\text{m}$ sample achieved 69.33%. Extending the leaching duration to 48 hours resulted in a slight decrease in recovery, indicating that equilibrium or near-equilibrium conditions were approached within 30 hours under the applied operational parameters.

Table 5. Leach test results (gold data)

Leaching time (hr)	$P_{60} = 75 \mu\text{m}$	Metal Recovered		$P_{80} = 75 \mu\text{m}$	Metal Recovered	
	Au in Leach (mg/L)	Au (mg)	Au (%)	Au in Leach (mg/L)	Au (mg)	Au (%)
0	-	-	-	-	-	-
2	606.43	606.43	44.26	509.58	509.58	37.20
4	771.00	781.18	57.02	643.68	652.23	47.61
6	834.40	857.43	62.59	723.00	742.35	54.19
24	943.95	980.98	71.60	903.35	934.75	68.23
30	985.68	1038.98	75.84	902.80	949.78	69.33
48	946.08	1016.03	74.16	887.04	949.27	69.29
total	-	1370.00	-	-	1370.00	-

The evolution of gold recovery as a function of leaching time and grinding fineness is illustrated in Figure 2, which clearly demonstrates the divergence in extraction efficiency between the two particle size distributions after the initial dissolution stage. Correspondingly, the variation in free cyanide concentration during leaching is presented in Figure 3, highlighting periodic cyanide depletion followed by incremental reagent additions that stabilized the chemical environment.

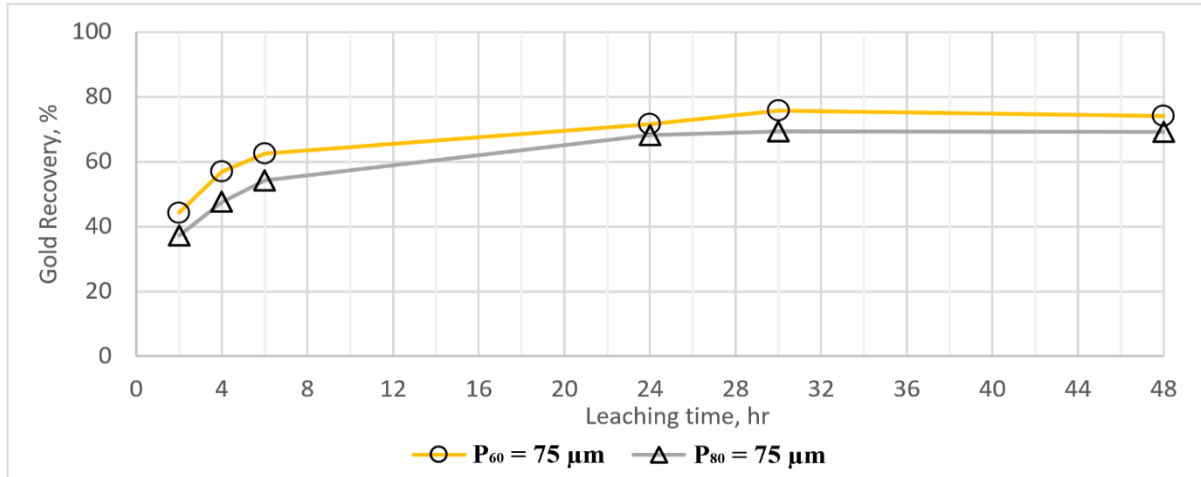


Figure 2. Gold recovery as a function of leaching time

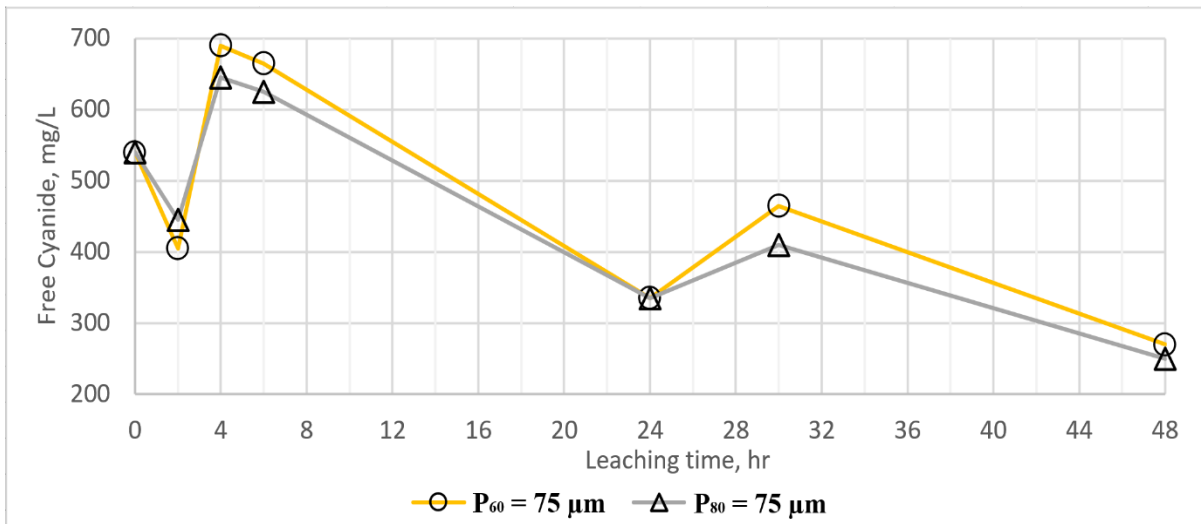


Figure 3. Free cyanide concentration during leaching

The observed kinetic behavior is consistent with diffusion-controlled or surface-reaction-limited dissolution mechanisms reported in cyanidation studies (Egan et al., 2016; Han et al., 2024). The controlled reagent dosing strategy ensured sufficient cyanide availability without excessive overconsumption.

Influence of Grinding Fineness

Although industrial practice often associates finer grinding with enhanced gold recovery due to improved liberation, the present results indicate that excessive size reduction does not necessarily improve gold recovery. Despite the finer particle distribution in the $P_{80} = 75 \mu\text{m}$ sample, the maximum recovery remained lower than that achieved at $P_{60} = 75 \mu\text{m}$ (Table 5).

This behavior may be attributed to overgrinding effects, including increased pulp viscosity and diffusion limitations arising from the formation of fine-grained particles that may act as a passivation layer. Fine particles can adversely affect slurry rheology and reduce effective oxygen mass transfer, thereby diminishing gold dissolution despite the increased surface area.

A comparative summary of maximum gold recovery and reagent consumption is presented in Table 6, which demonstrates that the higher recovery achieved at $P_{60} = 75 \mu\text{m}$ corresponds to slightly more effective cyanide utilization. These findings highlight the necessity of balancing particle size optimization with hydrodynamic and mass transfer considerations.

Table 6. Au recovery and reagent consumption

Parameter	$P_{60} = 75 \mu\text{m}$	$P_{80} = 75 \mu\text{m}$
Max. Au Recovery (%)	75.84	69.33
NaCN Consumption (kg NaCN per tonne of ore)	2.98	2.95
Lime Consumption (kg CaO per tonne of ore)	0.37	0.37

Such behavior is consistent with literature reports emphasizing that cyanidation efficiency depends on the coupled interaction of particle size, reagent concentration, oxygen availability, and pH stability rather than on grinding fineness alone (Azizi & Ghaedrahmati, 2015; Egan et al., 2016; Han et al., 2024; Shi, 2024; Banurea et al., 2025).

Process Implications

Overall, the integrated analysis of kinetic data (Tables 4 and 5), reagent consumption patterns (Table 6), and cyanide stability profiles (Table 3; Figure 3) confirms that optimal gold recovery under the investigated conditions was achieved at $P_{60} = 75 \mu\text{m}$ and 30 hours of leaching. The pilot-scale system enabled stable control of hydrodynamic and chemical parameters, thereby generating reproducible data suitable for kinetic modeling and pre-industrial optimization studies.

The consistency of recovery trends across successive sampling intervals, together with the stable pH and free cyanide profiles observed throughout the experiments (Table 3; Figure 3), indicates high reproducibility of the applied methodology. No anomalous fluctuations in dissolution kinetics were detected between the two experimental series, confirming the operational stability and reliability of the pilot-scale installation under controlled hydrodynamic and chemical conditions.

Conclusion

The experimental program confirmed that the designed and commissioned pilot-scale installation for agitated cyanidation provides stable hydrodynamic conditions, controlled reagent dosing, and reproducible operational performance. Under identical leaching parameters, maximum gold recovery was achieved after 30 hours, with superior extraction efficiency observed at $P_{60} = 75 \mu\text{m}$ compared to $P_{80} = 75 \mu\text{m}$, highlighting the importance of balanced particle size optimization.

The system enables continuous operation for up to 168 hours, simultaneous testing of five independent samples, and automated monitoring with minimal operator intervention. These features ensure high experimental reliability and reduce variability associated with manual process control. The obtained results demonstrate that gold dissolution efficiency is governed by the coupled interaction of particle size distribution, cyanide availability,

aeration conditions, and pH stability. The developed installation provides a robust experimental platform for kinetic evaluation and reagent optimization, with strong potential for extrapolation toward semi-industrial and industrial cyanidation circuits. Overall, the proposed system bridges laboratory-scale experimentation and industrial application, supporting improved process control and technological efficiency in gold hydrometallurgical operations.

Scientific Ethics Declaration

* The authors declare that the scientific, ethical, and legal responsibility for this article belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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Author(s) Information

Nikolay Nestorov

University of Mining and Geology “St. Ivan Rilski”
Prof. Boyan Kamenov Str., Sofia, Bulgaria
ORCID iD: <https://orcid.org/0009-0008-6543-8771>

*Contact e-mail: n.nestorov@mgu.bg

Irena Grigorova

University of Mining and Geology “St. Ivan Rilski”
Prof. Boyan Kamenov Str., Sofia, Bulgaria
ORCID iD: <https://orcid.org/0000-0002-8243-6232>

*Corresponding author(s) email

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Improving Accuracy of OWASP Dependency-Check Through Optimized CPE Matching to Reduce False Positives and False Negatives

Wahyu Francesco Toldo Hutabarat
Bandung Institute of Technology

Yani Widyani
Bandung Institute of Technology

Abstract: In today's digital era, the use of open-source dependencies in modern software development has become commonplace. However, this practice increases security risks due to vulnerabilities hidden within the open-source components being used. Software Composition Analysis (SCA) is one of the approaches that can be utilized to detect and mitigate the risks arising from the use of open-source dependencies. Nevertheless, existing SCA tools still face a fundamental challenge in the form of false positives (reported vulnerabilities that are not actually relevant) and false negatives (vulnerabilities that remain undetected), which can degrade the accuracy of detection results and hinder security analysis as well as mitigation decisions. This study focuses on improving the accuracy of one widely used SCA tool, OWASP Dependency-Check, by highlighting one of its main sources of error: the Common Platform Enumeration (CPE) matching process between project dependencies and vulnerability entries in the Common Vulnerabilities and Exposures (CVE) database. The objectives of this research are to analyze CPE matching error patterns, design optimization mechanisms to improve the matching process, and evaluate the impact of these optimizations.

Keywords: Software composition analysis, Dependency-check, Open-source security, CPE matching, Vulnerability detection, Software engineering

Introduction

The use of open-source software (OSS) has become an essential part of modern software development. Many systems rely on external libraries and frameworks to accelerate development and reduce cost. However, this practice also introduces security risks, as vulnerabilities in third-party components can propagate across the software supply chain and affect the overall system security (Shu et al., 2025). As software systems become more complex, managing these risks has become a critical challenge.

Software Composition Analysis (SCA) tools are widely used to identify dependencies and detect known vulnerabilities in OSS components. These tools analyze project structures, extract dependency information, and match them with vulnerability databases such as the National Vulnerability Database (NVD) (Shu et al., 2025). One commonly used tool is OWASP Dependency-Check, which maps dependencies to vulnerabilities using the Common Platform Enumeration (CPE) format. Despite their importance, previous studies have shown that SCA tools still face significant accuracy issues, including false positives and false negatives (Imtiaz et al., 2021; Zhao et al., 2023). Existing research has mainly focused on improving detection techniques, such as enhancing static analysis, applying machine learning, or combining multiple analysis approaches. While these methods can improve detection performance, they often overlook the complexity of real-world scenarios, such as multi-language ecosystems, binary dependencies, and adversarial conditions (Shu et al., 2025). As a result, SCA tools may perform well in controlled environments but fail to maintain accuracy in more complex situations.

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One critical component that is often overlooked is the matching process between detected dependencies and vulnerability records. In SCA tools, this process usually relies on heuristic-based CPE matching, including string similarity, vendor matching, and product name matching. However, these approaches can produce incorrect associations, especially when multiple candidate CPE entries exist. This may lead to irrelevant vulnerabilities being included (false positives) or relevant ones being missed (false negatives).

The limitations of current SCA tools indicate that accuracy issues are not only caused by detection weaknesses but also by problems in the matching mechanism. As highlighted by Shu et al. (2025), SCA tools still struggle to balance precision, recall, and robustness, particularly in complex environments. This suggests that improving only the detection stage is not sufficient to achieve reliable results. However, limited studies have specifically examined the impact of CPE matching accuracy on SCA results. Most research treats the matching process as a secondary step, even though it plays a key role as a bridge between dependency identification and vulnerability reporting. This creates a research gap, as improving the matching process has the potential to significantly enhance overall accuracy without modifying the detection engine.

The objectives of this research are threefold. First, to analyze common error patterns in the existing CPE matching mechanism. Second, to design an optimized matching approach. Third, to evaluate the effectiveness of the proposed approach using a ground truth dataset derived from the National Vulnerability Database. The proposed matching approach is implemented through four main components: artifact normalization, vendor prioritization, similarity scoring, and version filtering.

The results of this study demonstrate that optimizing the CPE matching process can significantly reduce false positives and false negatives and produce results that are closer to the ground truth. This finding highlights the importance of the matching layer in SCA systems and suggests that future improvements should consider both detection and matching mechanisms to achieve better accuracy.

Method

This study adopts an experimental approach to evaluate and improve the accuracy of vulnerability detection in SCA. The focus is on analyzing and optimizing the CPE matching process used by OWASP Dependency-Check. The method consists of four main stages: data collection, baseline extraction, ground truth construction, and optimized matching with evaluation.

Figure 1 illustrates the overall workflow of the proposed method. The process starts with data collection and baseline extraction using OWASP Dependency-Check. Then, a ground truth dataset is constructed from the NVD. After that, error analysis is performed by comparing baseline results with the ground truth to identify false positives and false negatives. Based on this analysis, the CPE matching process is optimized using four main components. Finally, the results are evaluated by comparing the detection accuracy before and after optimization.

Data Collection

The data used in this study consists of several open-source Java projects obtained from publicly available repositories. The selected projects include Apache Tomcat, Apache HttpClient, Mockito, Apache Commons Lang, Gson, Log4j, Jackson Databind, Netty, and Apache Struts. These projects were chosen to represent a diverse set of software dependencies, including widely used frameworks, utility libraries, and components with known vulnerability histories. The selection was not based on predefined error characteristics, but rather to ensure variation in project size, dependency structure, and usage context. For each project, vulnerability data is collected using OWASP Dependency-Check, which generates a JSON report containing detected dependencies and associated CVE entries. This report serves as the baseline data for further analysis.

In addition, vulnerability data from the National Vulnerability Database (NVD) is collected to construct a ground truth dataset. The ground truth is generated using exact CPE matching and version constraints to identify vulnerabilities that are truly applicable to each dependency. This combination of baseline data and ground truth enables a comparative evaluation of detection accuracy before and after the proposed CPE matching optimization.

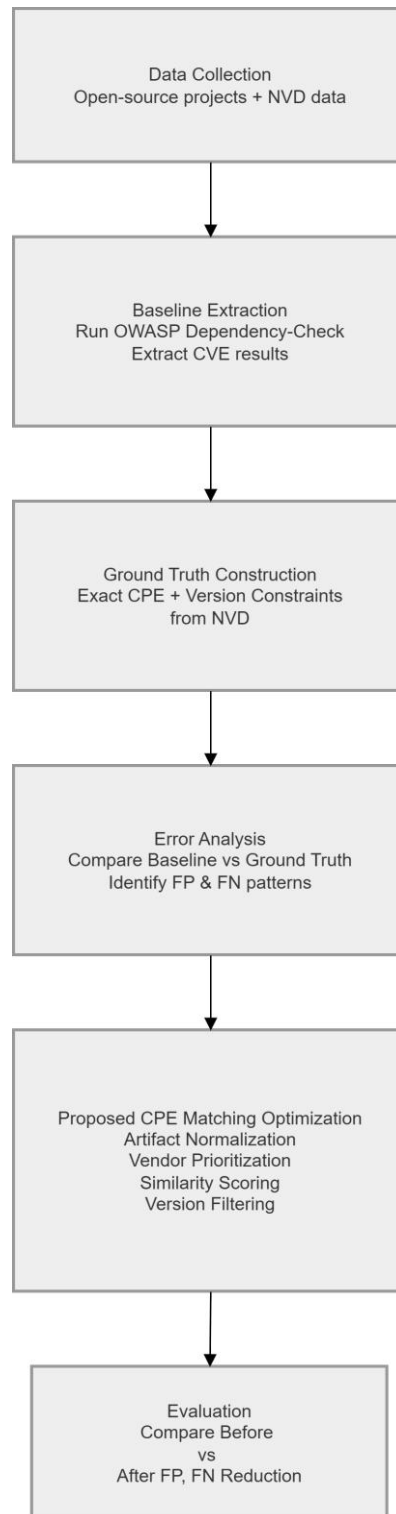


Figure 1. Proposed CPE matching workflow

Baseline Extraction

The first step is to extract vulnerability data from the raw output of the SCA tool. The JSON report generated by OWASP Dependency-Check is processed using a custom script ([extract_odc.py](#)) to retrieve all reported CVE entries for each dependency. Two types of data are collected:

- Total CVE entries (including duplicates),
- Unique CVE identifiers.

This step provides the baseline result of the SCA tool, which is later used for comparison with the optimized results.

Ground Truth Construction

To evaluate the accuracy of the SCA results, a ground truth dataset is constructed using vulnerability data from the National Vulnerability Database. The ground truth is generated using a custom script ([build_ground_truth.py](#)) based on the following criteria:

- exact matching of vendor, product, and version using the Common Platform Enumeration format,
- filtering based on version constraints such as versionStartIncluding and versionEndExcluding,
- inclusion of only vulnerabilities that are explicitly associated with the target software component.

This approach ensures that the ground truth represents a reliable reference for identifying valid vulnerabilities for each dependency.

Proposed CPE Matching Optimization

The core contribution of this study lies in improving the CPE matching process. The optimization is implemented using a custom script ([enhanced_odc_matcher.py](#)) that refines the mapping between dependencies and vulnerability entries.

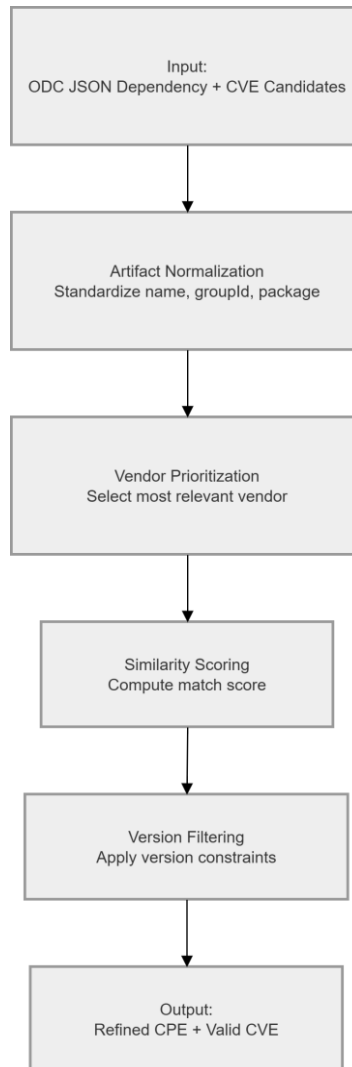


Figure 2. CPE matching optimization components

The proposed optimization consists of four main components, as shown in Figure 2. First, artifact normalization standardizes dependency metadata extracted from the OWASP Dependency-Check JSON report into a consistent format aligned with CPE representation. Second, vendor prioritization selects the most relevant vendor using rule-based mapping from groupId and known ecosystem patterns. Third, similarity scoring evaluates the relevance between dependency attributes and candidate CPE entries using a weighted scoring function based on name, vendor, and product similarity. Finally, version filtering ensures that only vulnerabilities applicable to the specific dependency version are retained based on version constraints from the NVD.

Artifact Normalization

This step standardizes the representation of metadata dependency information from JSON OWASP, including groupId, artifactId, name. The goal is to reduce inconsistencies between dependency metadata and CPE naming conventions, which often lead to incorrect matching.

Example (Before Normalization):

```
{
  "groupId": "org.apache.commons",
  "artifactId": "commons-lang3",
  "name": "commons-lang3-3.17.0.jar"
}
```

After Normalization:

```
vendor = apache
product = commons_lang
version = 3.17.0
```

Proposed Standard representation:

```
<vendor>:<product>:<version>
example: apache:commons_lang:3.17.0
```

Vendor Prioritization

In many cases, a dependency can be associated with multiple potential vendors in the CPE database. This component introduces a prioritization mechanism to select the most relevant vendor based on contextual information from the dependency, such as groupId and known ecosystem mappings. This helps reduce incorrect associations with unrelated vendors.

Example Candidates :

```
cpe:apache:commons_lang
cpe:oracle:commons_lang
cpe:netapp:commons_lang
```

This step uses a rule-based mapping. Vendor is selected based on GroupId.

Example rule:

```
org.apache.* → vendor = apache
com.fasterxml.* → vendor = fasterxml
```

Example:

```
groupId = org.apache.commons

The selected vendor is apache
```

Similarity Scoring

A similarity scoring mechanism is applied to evaluate the relevance between dependency attributes and candidate CPE entries. The weights are assigned using a heuristic approach, where the dependency name is considered the most important factor, followed by the vendor and the product. This is because the name usually provides the strongest indication of the correct match. The selected weights can be adjusted and further refined in future experiments.

Scoring Formula :

$$\text{Score} = 0.5 \times \text{Similarity}_{\text{name}} + 0.3 \times \text{Similarity}_{\text{vendor}} + 0.2 \times \text{Similarity}_{\text{product}}$$

Example:

Dependency: commons-lang3

CPE: commons_lang

Name similarity ≈ 0.9

Vendor match = 1

Product similarity ≈ 0.9

$$\text{Score} = (0.5 \times 0.9) + (0.3 \times 1) + (0.2 \times 0.9) = 0.93$$

From the remaining candidates, the system selects the most representative CPE based on the highest valid score and contextual validation. Only the best candidate is selected.

Version Filtering

This step ensures that the matched vulnerabilities are applicable to the specific version of the dependency. Version constraints from the vulnerability database, such as versionStartIncluding and versionEndExcluding, are used to filter out irrelevant vulnerabilities that fall outside the valid version range.

Example from NVD:

versionStartIncluding = 2.0

versionEndExcluding = 3.0

Dependency Version

Version = 3.17.0 (not in range, then removed)

Version = 2.5 (In range, valid)

Only vulnerabilities that match the dependency version are retained.

Results and Discussion

Baseline vs Optimized Results

This section presents the comparison between the baseline results produced by OWASP Dependency-Check and the optimized results obtained using the proposed CPE matching approach. The evaluation is conducted across multiple open-source projects with varying characteristics.

Overall, the results show that the proposed method significantly improves the accuracy of vulnerability detection by reducing both false positives and false negatives. In several cases, the optimized results are fully aligned with the ground truth derived from the [National Vulnerability Database](#).

The impact of the proposed CPE matching optimization on reducing false positives is presented in Table 1. Table 1 shows the comparison of false positive results before and after applying the optimized CPE matching method. In the baseline OWASP Dependency-Check, several datasets produced high false positive rates, such as Mockito and Struts, which reached 100%, and Commons Lang with 80%. After applying the optimization, all false positives were successfully removed across all datasets. This indicates that the proposed method can effectively filter irrelevant vulnerabilities and improve the accuracy of vulnerability detection.

Table 1. False positive reduction after optimization

Project	Baseline CVE Before	Ground Truth	FP Before	FP (%) Before	Enhance CVE After	FP (After)	FP (%) After
Tomcat 7.0.0	85	74	11	12.94%	74	0	0%
Mockito 5.15.0	4	0	4	100%	0	0	0%
Commons Lang 3.17.0	5	1	4	80%	1	0	0%
Jackson 2.4.0	48	47	1	2.08%	47	0	0%
Struts 2.3.1.1	6	0	6	100%	0	0	0%

After applying the proposed optimization, all false positives are successfully eliminated across all evaluated datasets, resulting in a false positive rate of 0%. This demonstrates that the optimized CPE matching approach is effective in filtering out irrelevant vulnerability matches by enforcing stricter validation on vendor, product, and version attributes. Consequently, the overall precision of the vulnerability detection process is significantly improved.

Table 2. False negative reduction after optimization

Project	Baseline CVE Before	Ground Truth	FN Before	FN (%) Before	Enhance CVE After	FN (After)	FN (%) After
Gson 2.8.0	0	1	1	100%	0	0	0%
Netty 3.9.0	0	3	3	100%	0	0	0%

The optimized CPE matching approach not only reduces false positives but also eliminates false negatives, ensuring that all relevant vulnerabilities are correctly identified. Table 2 shows the comparison of false negative results before and after applying the optimized method. In the baseline OWASP Dependency-Check, both Gson and Netty datasets failed to detect existing vulnerabilities, resulting in a false negative rate of 100%. After applying the optimization, all false negatives were successfully eliminated. This demonstrates that the proposed method improves the ability to identify vulnerabilities that were previously missed.

Conclusion

The proposed optimization consists of four main components, as shown in Figure 2. First, artifact normalization standardizes dependency metadata extracted from the OWASP Dependency-Check JSON report into a consistent format aligned with CPE representation. Second, vendor prioritization selects the most relevant vendor using rule-based mapping from groupId and known ecosystem patterns. Third, similarity scoring evaluates the relevance between dependency attributes and candidate CPE entries using a weighted scoring function based on name, vendor, and product similarity. Finally, version filtering ensures that only vulnerabilities applicable to the specific dependency version are retained based on version constraints from the NVD. This result indicates that the main source of error in OWASP Dependency-Check lies in the CPE matching stage rather than the detection stage. However, the approach relies on rule-based mapping, which may require adaptation for different ecosystems. The system selects only one most representative CPE from the remaining candidates based on the highest valid score.

Recommendations

Future work can evaluate the proposed method on larger and more complex software projects to test its scalability and robustness. Although the results show strong improvements, the current approach is mainly based on rule-based matching and predefined normalization strategies. Therefore, more advanced techniques, such as semantic analysis or machine learning, can be explored to handle more complex and ambiguous cases that are not covered by the current rules. In addition, integrating the proposed method into existing SCA tools can help improve their practical performance in real-world environments.

Scientific Ethics Declaration

* The authors declare that the scientific and ethical responsibility of this article belongs to the authors. This study does not involve human participants or animals and therefore does not require ethical approval.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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Author(s) Information

Wahyu Francesco Toldo Hutabarat

Bandung Institute of Technology
Jl. Ganesa No. 10, Indonesia
ORCID iD: <https://orcid.org/0009-0004-9447-3446>
*Contact e-mail: 23524028@mahasiswa.itb.ac.id

Yani Widayani

Bandung Institute of Technology
Jl. Ganesa No. 10, Indonesia
ORCID iD: <https://orcid.org/0000-0002-8510-003X>

*Corresponding author(s) email

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Integrating Bayesian Inference with BP-Transformer for Accurate Traffic Flow Prediction

Anastasia Feofilova

Don State Technical University

Viacheslav Fialkin

Don State Technical University

Jixiao Jiang

Don State Technical University

Abstract: Nonlinear fluctuations and abrupt events in traffic flow can lead to significant point prediction errors, thereby limiting the effectiveness of traffic control strategies in Intelligent Transportation Systems (ITS). To address this issue, we propose a novel hybrid deep learning model, Bayes-BP-Transformer. This model combines Bayesian inference with backpropagation and a Transformer architecture, improving prediction accuracy while maintaining the model's generalization ability. Specifically, the backpropagation component captures local temporal patterns, while the Transformer encoder models long-range spatiotemporal dependencies. By introducing Bayesian inference, the model optimizes the probability distribution of network weights, improving robustness to noise and incomplete data. Experiments on two real-world traffic datasets demonstrate the superior performance of our model. Compared to advanced models, Bayes-BP-Transformer reduces the root mean square error (RMSE) by 18.6-38.0% and the mean absolute percentage error (MAPE) by 5.7-32.9%. Therefore, this model provides a feasible approach for building reliable prediction systems in ITS.

Keywords: Traffic flow prediction, Spatio-temporal modeling, Transformer, Intelligent Transportation Systems

Introduction

Traffic flow data, as a typical spatiotemporal sequence, is generated by the combined influence of road network topology, driving behavior, signal control, and various unforeseen events (Zhang et al., 2025). This convergence of multiple factors results in highly non-stationary and spatiotemporally heterogeneous traffic flow, posing a continuous challenge to accurate prediction. Single deep learning models, such as CNNs and their variants, cannot simultaneously capture the spatiotemporal dependencies present in the road network (Yang et al., 2025). Currently, complex deep learning models such as Temporal Convolutional Networks (TCNs) and Long Short-Term Memory Networks (LSTMs) have achieved extremely high prediction accuracy in various real-world prediction scenarios by precisely capturing the abrupt changes and temporal dependencies of traffic flow (Jiang et al., 2026). However, these models rely on large amounts of historical data for training (Topilin et al., 2025). When data is sparse or unconventional traffic patterns occur, their generalization ability often declines. Secondly, models like TCNs and LSTMs are essentially point prediction models (Wang et al., 2025). In scenarios where traffic flow fluctuates dramatically and exhibits non-linear changes, the prediction results are unreliable due to the lack of visualized prediction parameters, thus affecting the robustness of traffic control strategies.

To address these challenges, researchers are attempting to incorporate optimization algorithms or attention mechanisms into the models to enhance the accuracy and interpretability of predictions (Dai & Tang, 2025). For example, Ali et al. (2025) record prediction accuracy by combining Gated Recurrent Units (GRUs) and Graph

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Convolutional Networks (GCNs) to record spatial and temporal variation characteristics. Wu et al. (2026) demonstrated that dynamic graph convolutional networks combined with attention mechanisms can effectively capture real-time changes in road network topology to achieve efficient prediction. Tian et al. (2025) analyzed the randomness of traffic flow at road intersections by fusing the Sparrow Search Algorithm (SSA) with the Deep Extreme Learning Machine (DELM) and finally obtained the best fitting effect in the experiment. However, these models generally exhibit a strong dependence on high-quality historical data. Furthermore, multi-module fusion models come with high computational costs. In real-world deployment scenarios requiring real-time responses, issues such as long training times and complex parameter tuning limit their practicality in road networks.

To overcome these limitations, we propose a novel hybrid deep learning model, Bayes-BP-Transformer. The BP component, a lightweight yet efficient module, extracts local temporal features. Compared to recurrent architectures like LSTM, the BP network offers lower computational overhead and faster training speed, making it more suitable for real-time deployments. The Transformer encoder captures long-range spatiotemporal dependencies through its multi-head self-attention mechanism. Unlike TCNs, which are limited by fixed receptive fields, the Transformer can dynamically weight the importance of different time steps and spatial locations, enabling more flexible modeling of complex traffic patterns. The Bayesian framework incorporates uncertainty into the learning process by setting probability distributions on the network weights instead of learning fixed values. The core innovation of Bayes-BP-Transformer lies in its seamless integration of deterministic feature extraction and inference. Pure Bayesian models often struggle to balance scalability and computational efficiency when applied to high-dimensional traffic data. Our method addresses this deficiency by embedding Bayesian layers within the BP-Transformer backbone, achieving a balance between representational power and uncertainty perception. This design ensures that the model remains computationally feasible in real-time applications, while providing more stable predictions under fluctuating traffic conditions.

Method

Overall Model Framework

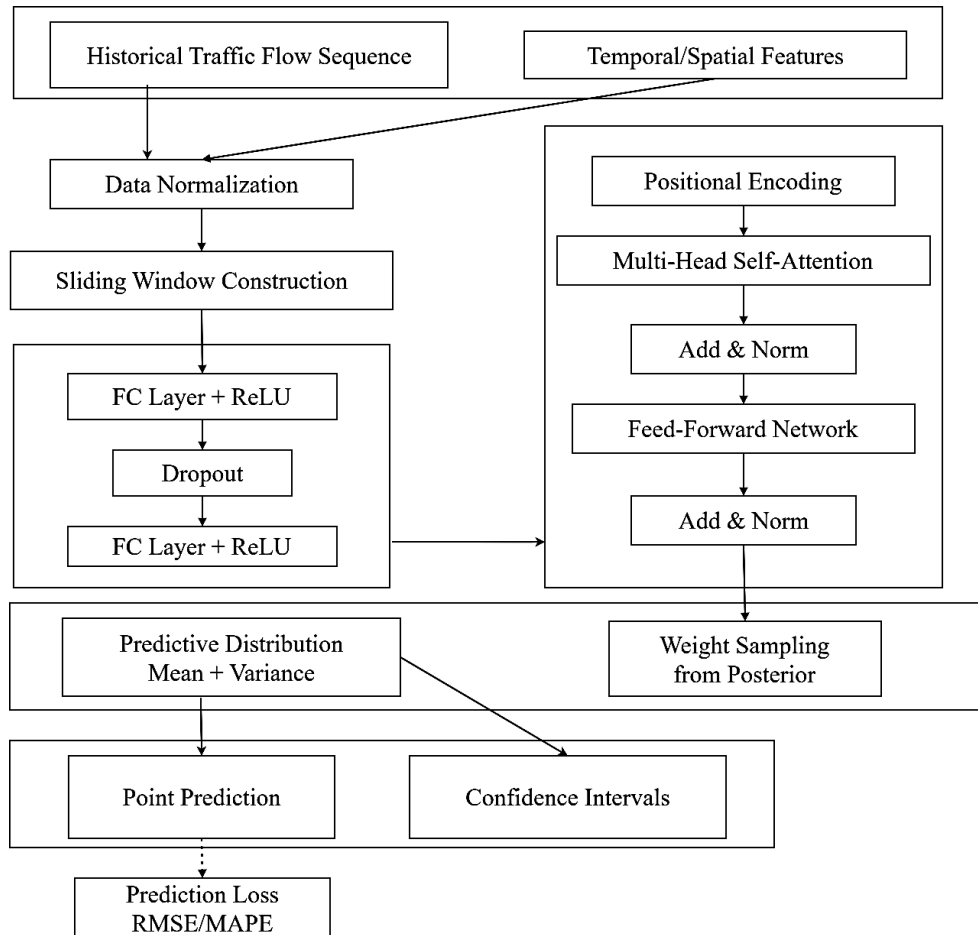


Figure 1. Bayes-BP-Transformer overall framework and process

The overall flow of the Bayes-BP-Transformer model is shown in Figure 1. Historical traffic flow sequences and spatiotemporal features are first normalized and input into the BP module, where local temporal features are extracted through two fully connected layers and Dropout operations. Subsequently, these features are fed into the Transformer encoder, passing through position encoding, multi-head self-attention mechanism, residual connections, and a feedforward network to dynamically model long-range spatiotemporal dependencies. The Transformer output enters the Bayesian inference layer, where the mean and variance of the predicted distribution are obtained by posterior sampling of the network weights. Finally, the model jointly optimizes the prediction error during training, improving the model's generalization ability while ensuring prediction accuracy.

BP-Transformer Module Modeling

The BP module is the first stage of the Bayes-BP-Transformer model, responsible for extracting local temporal features from the preprocessed input data. This module acts as a learnable input embedding layer, projecting raw traffic features into a high-dimensional space that facilitates subsequent temporal dependency modeling by the Transformer encoder. This module consists of two fully connected layers with a Dropout layer inserted in between to prevent overfitting, and each fully connected layer is followed by a ReLU activation function to introduce a nonlinear transformation. Let the traffic flow data input to the BP module be X , and the operation of flattening the input X into a vector x is represented by Equation 1.

$$x = \text{Flatten}(X) \quad (1)$$

The computation of the first fully connected layer is represented by Equation 2.

$$h_1 = \text{ReLU}(W_1 x + b_1) \quad (2)$$

where W_1 denotes the weight matrix, b_1 denotes the bias term, and ReLU denotes the activation function.

To mitigate overfitting in the BP module, Dropout is applied to the output of the first layer. This process is represented by Equation 3.

$$h_1^{drop} = \text{Dropout}(h_1, p) \quad (3)$$

where p denotes the neuron dropout probability.

The operation of the second fully connected layer of the BP module for further extracting traffic flow features is represented by Equation 4.

$$h_2 = \text{ReLU}(W_2 h_1 + b_2) \quad (4)$$

where W_2 denotes the weight matrix of the second fully connected layer, and b_2 denotes the bias term.

Finally, the BP module outputs the local temporal features obtained from the fully connected layer, which are then passed to the subsequent Transformer encoder for further processing. The operation flow of the Transformer encoder is shown in Figure 2.

The Transformer encoder consists of L identical layers stacked together. Each layer contains a multi-head self-attention mechanism and a feedforward network, with residual connections and layer normalization following each sub-layer. The calculation of the attention output of the L th layer is shown in Equation 5.

$$A = \text{softmax}\left(\frac{z_0 W^\varphi \cdot K^T}{\sqrt{d_k}}\right) \cdot V \quad (5)$$

where z_0 denotes the Transformer's positional encoding, W^φ denotes the learnable weight matrix, T denotes the historical time steps, d denotes the dimension of each attention head, and K and V denote the attention weight matrices.

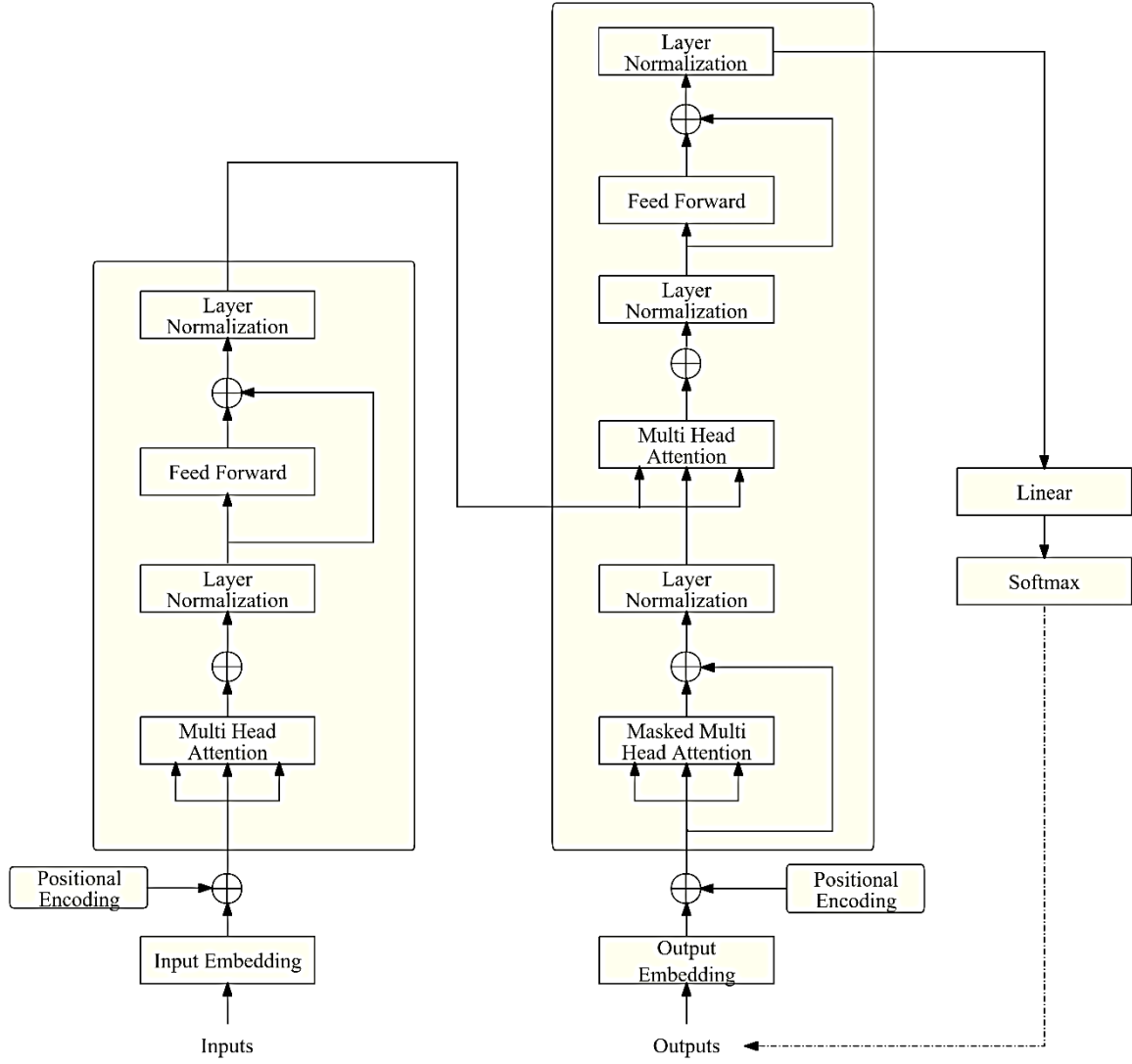


Figure 2. Transformer encoder operation flow

The subsequent operation of adding residual connections and layer normalization to the Transformer is represented by Equation 6.

$$z_L = \text{LayerNorm}(z_{L-1} + A) \quad (6)$$

where z_{L-1} denotes the output of the $(L-1)$ th Transformer encoder, and LayerNorm denotes layer normalization.

After stacking L layers, the final output Z (Equation 7) serves as the spatiotemporal feature representation extracted by the Transformer encoder and is passed to the subsequent Bayesian inference module.

$$Z = \text{LayerNorm}(z_L + \text{ReLU}(W_L^{F_1} + b_L) \cdot W_L^{F_2}) \quad (7)$$

where $W_L^{F_1}$ and $W_L^{F_2}$ denote the feedforward network weight matrices, and b_L denotes the bias of the feedforward network weight matrix.

Bayesian Inference Module Modeling

The Bayesian inference module treats network weights as probability distributions and learns the posterior distribution of weights through variational inference during training, thereby effectively alleviating the overfitting problem. Its operation process is shown in Figure 3.

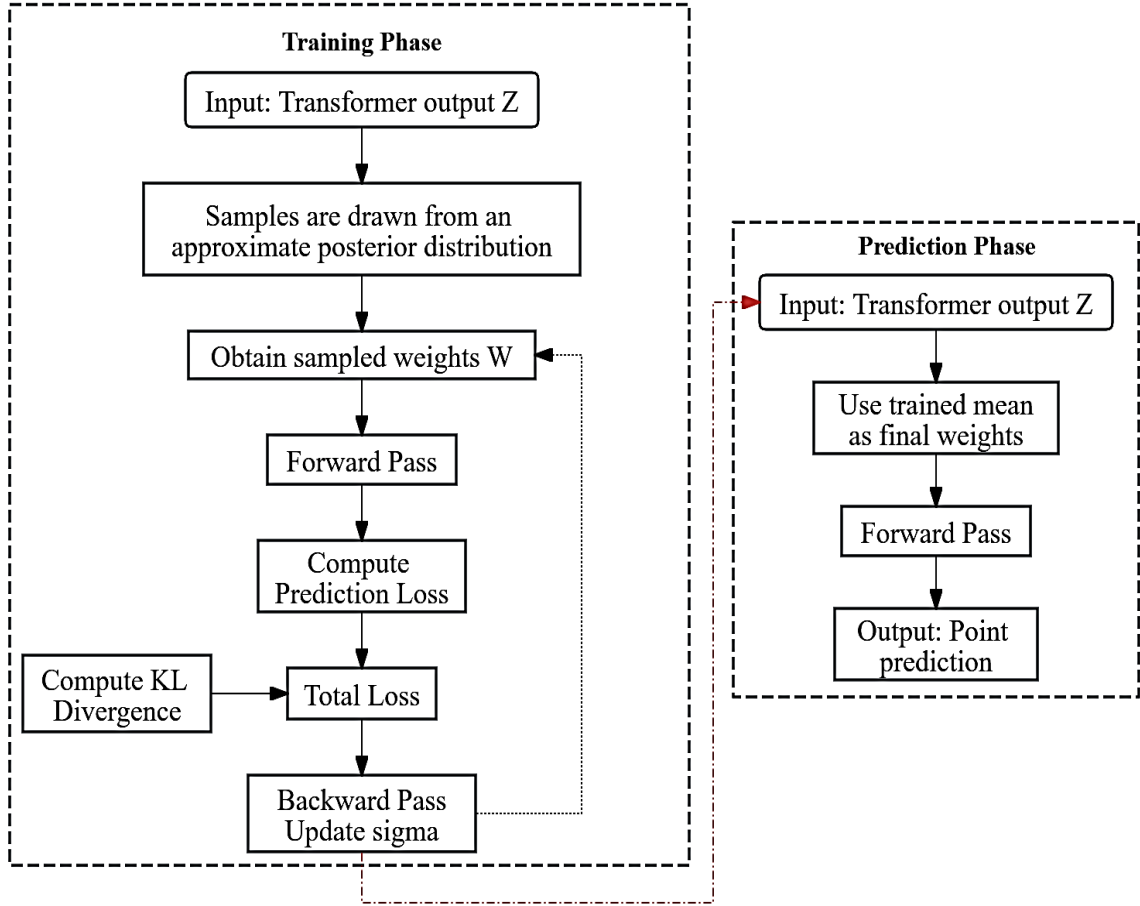


Figure 3. Bayesian inference module operation flow

The Bayesian module replaces traditional deterministic weights with probability distributions, where each weight is represented by the mean and log-variance (Equation 8).

$$W_T = \mu + \exp(\rho) \odot \varepsilon \quad (8)$$

where μ denotes the weight mean matrix, ρ denotes the log-standard deviation parameter, and ε denotes standard normal distribution noise.

The approximate posterior distribution of the weights is defined by Equation 9.

$$q(W_T | \mu, \rho) = \prod_{ij} N(W_{ij} | \mu_{ij}, \exp(\rho_{ij})^2) \quad (9)$$

where μ_{ij} denotes the mean of the weights, and $\exp(\rho_{ij})$ denotes the log-variance.

The expression for a single forward propagation is Equation 10.

$$y = \delta(z \cdot W_T + b) \quad (10)$$

where δ denotes the activation function, and b denotes the deterministic bias term.

The total loss function is defined as Equation 11.

$$L = \frac{1}{N} \sum (y_i - \hat{y}_i) + \sum \frac{(\mu^2 + \exp(2\rho) - 1 - 2\rho)}{2} \quad (11)$$

where $\sum(y_i - \hat{y}_i)$ denotes the KL divergence term, y_i denotes the true value of the i-th sample, and $\hat{y}_i$ denotes the predicted value of the i-th sample.

The entire model prediction output stage is represented by Equation 12.

$$\hat{y} = z \cdot \mu^T + b \quad (12)$$

where μ^T denotes the transpose of the mean matrix μ .

The three core modules of the Bayes-BP-Transformer model are connected in a serial cascade manner to form an end-to-end prediction framework. The modules work collaboratively to achieve a complete mapping from raw data to prediction results.

Prediction Experimental Verification

Experimental Data Selection

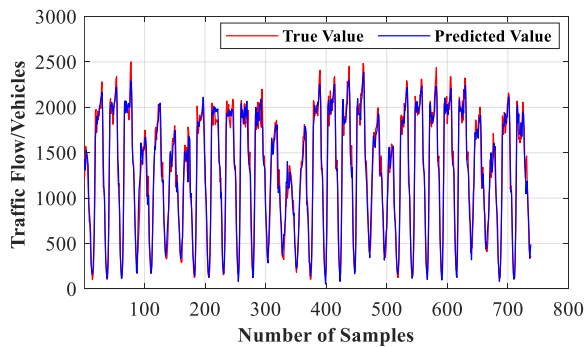
The experiments in this study were conducted in the MATLAB environment, utilizing its deep learning toolbox to construct, train, and validate the Bayes-BP-Transformer model. Both datasets used in the experiments were derived from a publicly available traffic flow database (UTD). The Paris long-term dataset was collected from 1-hour aggregated data from detector number 268 throughout May 2016, while the Turin short-term dataset was collected from 5-minute aggregated data from detector number 2255 on September 27, 2016.

The Paris dataset was chosen because the full-month, long-term data allows for thorough validation of the model's ability to capture multi-scale periodic dependencies. Detector 268, located on a core Parisian artery, experiences high and complex traffic flow patterns, placing higher demands on the model's generalization ability. Furthermore, the mixed patterns of numerous holidays and workdays in May allow for testing the model's robustness under unconventional traffic conditions.

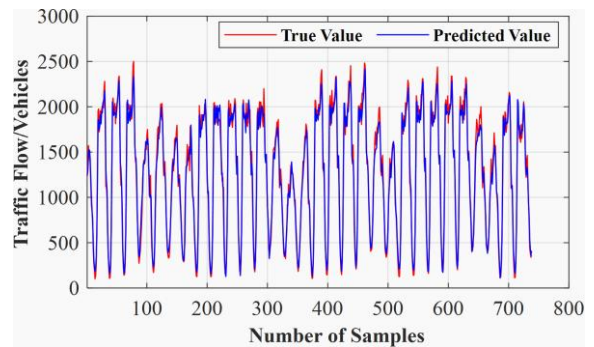
The Turin dataset was chosen because short-term single-day data can be used to verify the model's predictive performance under limited historical data conditions, simulating data-sparse scenarios in real-world applications. Furthermore, Turin, as a medium-sized city, has traffic flow characteristics that differ from Paris, which helps test the model's cross-city transferability.

Traffic Flow Prediction Experiment

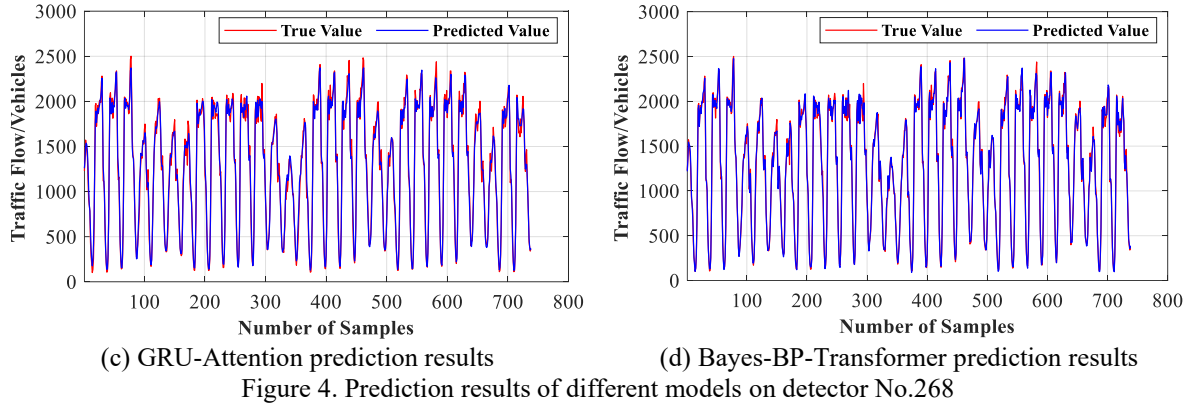
To objectively assess the model's level within existing research and provide a quantifiable benchmark for future studies, we compared it with the baseline model BP, as well as two advanced models: CNN-LSTM (Zhang et al., 2025) and GRU-Attention (Li et al., 2025). Figure 4 shows the data prediction results for detector 268 for each model.



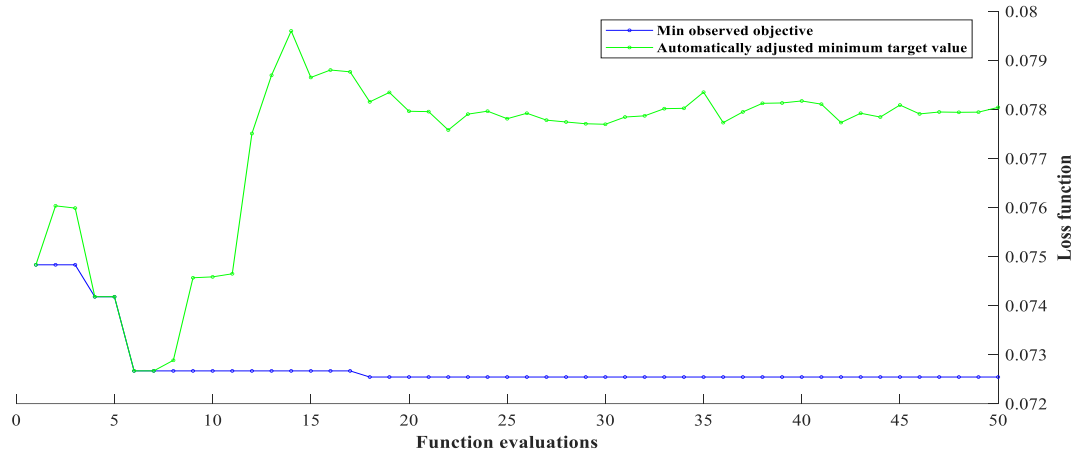
(a) BP prediction results



(b) CNN-LSTM prediction results



As shown in Figure 4, in the traffic flow prediction task of detector 268, the Bayes-BP-Transformer model performed best, while the BP model performed worst. This is because the BP model, as a single fully connected network, can only capture the static mapping relationship between input features. It cannot effectively model the temporal dependencies and dynamic changes in traffic flow data. The Bayes-BP-Transformer model, on the other hand, integrates the dynamic modeling of long-range spatiotemporal dependencies of the Transformer and adjusts the loss parameters through Bayesian inference, thus improving the model's generalization ability under complex traffic patterns. Figure 5 illustrates the process of adjusting the model's loss function through Bayesian inference.



As shown in Figure 5, Bayesian inference achieves the best prediction results by automatically finding the optimal loss function and effectively suppressing overfitting during training through KL divergence regularization.

Results and Discussion

To more intuitively compare the prediction accuracy of each model, we used RMSE and MAPE as evaluation metrics to assess the prediction data obtained by detectors 268 and 2255 (Jiang & Feofilova, 2025). The evaluation metrics for the prediction results are shown in Table 1.

Table 1. Evaluation metrics results for various models

Detector number	Model	RMSE	MAPE
No.268	BP	41.279	45.840
	CNN-LSTM	35.827	37.644
	GRU-Attention	28.523	30.131
	Bayes-BP-Transformer	22.195	28.427
	BP	44.128	47.015
No.2255	CNN-LSTM	37.603	39.280
	GRU-Attention	30.127	34.092
	Bayes-BP-Transformer	24.521	26.355

As shown in Table 1, the BP model performed the worst on the Paris dataset. CNN-LSTM improved performance through local feature extraction. GRU-Attention further enhanced prediction accuracy by introducing an attention mechanism. The proposed Bayes-BP-Transformer model achieved the best results across all metrics, reducing the RMSE by 22.2% compared to GRU-Attention. On the Turin dataset, the model performance ranking remained consistent, with Bayes-BP-Transformer again performing best, reducing RMSE by 18.6% and 22.7% compared to the second-best models, respectively. This advantage further demonstrates the Transformer's ability to capture long-range spatiotemporal dependencies, the robustness of Bayesian inference to noise, and the effective suppression of overfitting by KL divergence regularization.

Conclusion

This paper proposes a Bayes-BP-Transformer hybrid deep learning model for accurate and robust traffic flow prediction. This model combines Bayesian inference with a BP-Transformer backbone network, effectively capturing local temporal patterns and long-range spatiotemporal dependencies, and introduces probability weight distribution to enhance generalization ability and noise resistance. Experiments on two real-world datasets from Paris and Turin demonstrate that the proposed model consistently outperforms baseline models and advanced models, including BP, CNN-LSTM, and GRU-Attention. Specifically, depending on the dataset and the comparison models, the Bayes-BP-Transformer reduces the root mean square error (RMSE) by 18.6% to 38.0% and the mean absolute percentage error (MAPE) by 5.7% to 32.9%. Therefore, the Bayes-BP-Transformer provides a feasible and reliable method for building robust prediction systems in ITS applications. Despite its advantages, the model has certain limitations. The current architecture does not explicitly incorporate spatial graph structures, which may limit its performance in complex road networks. Additionally, the choice of prior distributions in the Bayesian layers remains an open area for further exploration.

Recommendations

Future research can extend this work in several directions. First, introducing GCN to explicitly model spatial dependencies in road network topology can further improve prediction performance. Second, exploring different prior distributions of Bayesian layers, such as slab-flat priors, can improve the sparsity and interpretability of the model. Third, applying the proposed framework to other spatiotemporal prediction tasks, such as travel time prediction or traffic speed prediction, can further validate its generalization ability. Finally, deploying the model into a real traffic management system and evaluating its impact on control strategies will help to gain a deeper understanding of its practical application effectiveness.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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Author(s) Information

Anastasia Feofilova

Don State Technical University
1, Gagarin Square, Rostov-on-Don, Russia
ORCID iD: <https://orcid.org/0000-0003-3351-4246>
*Contact e-mail: feofilowa@mail.ru

Viacheslav Fialkin

Don State Technical University
1, Gagarin Square, Rostov-on-Don, Russia
ORCID iD: <https://orcid.org/0000-0003-4332-9677>

Jixiao Jiang

Don State Technical University
1, Gagarin Square, Rostov-on-Don, Russia
ORCID iD: <https://orcid.org/0009-0009-4376-790X>

*Corresponding author(s) contact email

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Evaluation of a Plant Quality Monitoring System Based on Visible and Near-Infrared Spectroscopy Sensors in a Controlled Environment

Arifa Haryani

Gadjah Mada University

Andri Prima Nugroho

Gadjah Mada University

Nazmi Mat Nawi

Universiti Putra Malaysia

Mohammad Affan Fajar Falah

Gadjah Mada University

Lilik Sutiarto

Gadjah Mada University

Ardan Wiratmoko

Gadjah Mada University

Muhammad Athala Fawwaz Dzaky

Gadjah Mada University

Samuel Gatot Marseno

Gadjah Mada University

Abstract: The increasing demand for agricultural production requires reliable and non-destructive methods for monitoring plant physiological conditions in real time, particularly in controlled environments. Spectral sensing in the visible to near-infrared (VIS–NIR) region offers a promising approach; however, the performance of low-cost sensors is often limited by calibration accuracy, wavelength-dependent sensitivity, and insufficient validation against plant physiological indicators. This study aims to evaluate the performance of a VIS–NIR plant monitoring system based on the AS7265x multispectral sensor in a controlled hydroponic environment. Lettuce (*Lactuca sativa* L.) was grown under two nutrient concentrations (600 ppm and 1200 ppm), and spectral reflectance data were collected across the 410–760 nm range. Sensor measurements were calibrated and validated against a LI-COR LI-180 reference spectrometer using linear regression, with performance assessed using the coefficient of determination (R^2), root mean square error (RMSE), and spectral response consistency. The results show strong calibration performance, with wavelength-specific R^2 values ranging from 0.9682 to 0.9870 and RMSE values between 0.26965 and 5.19772. Although a systematic offset was observed, the AS7265x sensor preserved key spectral patterns, particularly in the green (510–560 nm) and red-edge (705–730 nm) regions. Differences in nutrient concentration were consistently reflected in both spectral responses and SPAD measurements, indicating sensitivity to plant physiological variations. These findings demonstrate that the AS7265x sensor provides reliable spectral information for relative plant monitoring and has strong potential as a cost-effective tool for plant quality assessment in controlled environments.

Keywords: AS7265x sensor, VIS–NIR spectroscopy, Spectral reflectance, Plant monitoring

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Introduction

Climate change and rapid population growth have significantly increased pressure on global agricultural systems, with food demand projected to rise alongside a global population reaching 9.7 billion by 2050 (Zhao et al., 2024). This situation intensifies the need for sustainable agricultural practices while minimizing environmental impacts caused by limited land and water resources (Sanyaolu & Sadowski, 2024). In response, precision agriculture has been developed to improve productivity and resource efficiency through data-driven management. A critical requirement within this approach is the ability to monitor plant physiological conditions accurately and continuously throughout the growth cycle.

Conventional plant quality assessment methods, such as laboratory-based biochemical analysis, are destructive, time-consuming, and costly. These limitations prevent their application for continuous and real-time monitoring, particularly in dynamic cultivation systems. As a result, they are not suitable for tracking plant responses during growth stages. Non-destructive sensing technologies are therefore required to enable continuous observation of plant conditions and to support timely decision-making in modern agricultural systems.

Controlled Environment Agriculture (CEA), including hydroponic systems and plant factories, has emerged as an effective strategy to reduce environmental variability and ensure stable crop production (Engler & Krarti, 2021). These systems enable precise regulation of environmental factors such as light, temperature, humidity, and nutrient supply, which enhances plant growth performance (Dsouza et al., 2023; Villagran et al., 2025). However, monitoring in CEA is still largely focused on environmental parameters rather than direct plant responses. This creates a limitation in understanding how plants physiologically respond to controlled conditions.

Advancements in plant phenotyping have introduced various sensor-based approaches to assess plant condition in a non-destructive manner (Jung & Arar, 2023). Several studies have integrated sensing technologies with computational methods to improve monitoring capabilities (Lolitasya et al., 2025; Dey & Ahmed, 2025). Despite these developments, existing systems often face challenges related to measurement instability, sensitivity to environmental variations, and high implementation costs (Bai et al., 2025). These constraints limit the practical application of such systems, particularly in controlled agricultural environments.

Spectroscopic techniques in the visible to near-infrared (VIS–NIR) region provide a promising solution for non-destructive plant monitoring. Reflectance signals in this spectral range are closely associated with plant physiological properties, including chlorophyll content, leaf structure, and nutrient status (Lazim et al., 2023). Specific wavelength regions, such as the green band (approximately 510–560 nm) and the red-edge region (approximately 705–730 nm), are highly sensitive to variations in chlorophyll concentration. These spectral characteristics have been widely utilized for assessing plant condition in agricultural applications (Atanassova et al., 2025).

Recent studies have explored the application of low-cost multispectral sensors, such as the AS7265x, for plant monitoring. Lopin et al. (2025) demonstrated the capability of the AS7265X sensor for non-destructive chlorophyll estimation based on spectral reflectance. However, previous systems were often limited to indirect measurements, such as photosynthetic photon flux density (PPFD), without direct validation against plant physiological parameters. This limitation reduces the interpretability of spectral data and constrains its use for plant quality assessment.

In addition, the performance of low-cost spectral sensors is often affected by calibration accuracy, wavelength-dependent sensitivity, and systematic bias relative to reference spectrometers. Without proper calibration, these sensors may produce inconsistent reflectance values across wavelengths. Furthermore, the relationship between spectral reflectance and physiological indicators, such as chlorophyll content, is not always explicitly validated. This condition limits the reliability of these systems for practical applications in precision agriculture.

The objective of this study is to evaluate the performance of a VIS–NIR plant monitoring system based on the AS7265x sensor in a controlled hydroponic environment by assessing its calibration accuracy, spectral response consistency, and its relationship with plant physiological status. The evaluation is conducted through comparison with a reference spectrometer and validation using SPAD measurements as an indicator of chlorophyll content. This approach ensures that both the technical performance of the sensor and its physiological relevance are systematically examined. The results of this study provide a structured evaluation of low-cost multispectral sensing for plant monitoring and contribute to improving the reliability of spectral measurements. The findings also support the application of VIS–NIR sensors for relative assessment of plant quality in controlled environments.

Method

Data Collection

This study was conducted at the Smart Agriculture Research Center, Department of Agricultural and Biosystems Engineering, Faculty of Agricultural Technology, Universitas Gadjah Mada. The monitoring system was implemented in a controlled environment using a SmartAgri growth chamber, where environmental variables such as temperature, humidity, light intensity, and nutrient supply were regulated. The overall experimental workflow, including calibration, data acquisition, validation, and evaluation processes, is illustrated in Figure 1.

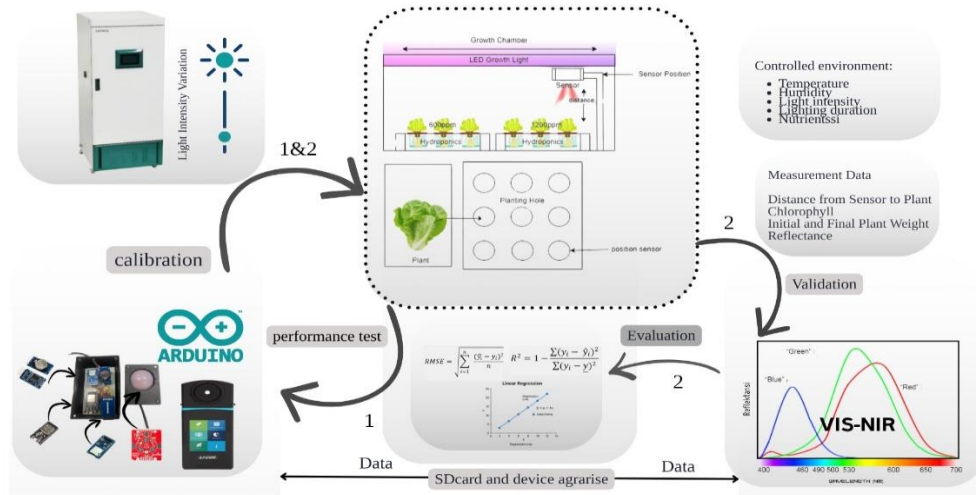


Figure 1. Conceptual framework of the VIS-NIR-based plant monitoring system, including calibration, acquisition, validation, and evaluation processes

The system integrates a VIS-NIR multispectral sensor (AS7265x), a LI-COR LI-180 reference spectrometer, and a microcontroller-based data acquisition unit. As shown in Figure 1, the calibration stage was performed using the reference spectrometer to establish a relationship between sensor output and standard spectral measurements. Data acquisition was conducted using lettuce plants at 28 days after transplanting, with reflectance values collected across intensity levels ranging from 10% to 100% at 5% increments to ensure sufficient calibration coverage.

The data acquisition algorithm and system operation flow are presented in Figure 2. The system was configured to automatically record spectral data within the 410–760 nm range at regular intervals. When connected to a network, data were transmitted to a cloud-based platform, while offline data were stored locally on a microSD card.

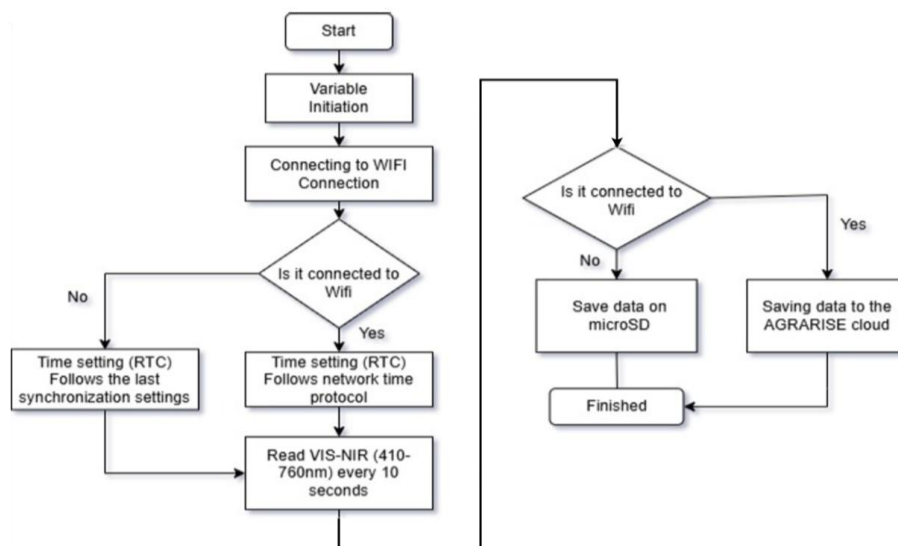


Figure 2. Flowchart of the VIS-NIR data acquisition and transmission algorithm

Model Evaluation

Linear regression analysis was applied to quantify the relationship between the AS7265x sensor measurements and the LI-COR LI-180 reference data. In this model, spectral reflectance obtained from the AS7265x sensor was defined as the dependent variable, while the reference measurements were treated as the independent variable. This approach enables the development of calibration equations to reduce systematic differences between sensors

The performance of the regression model was evaluated using the coefficient of determination (R^2), as defined in Equation (1). This metric represents the proportion of variance in the reference data that can be explained by the calibrated sensor output. Higher R^2 values indicate stronger agreement between the sensor and the reference instrument.

$$R^2 = 1 - \frac{\sum (y_i - \hat{y}_i)^2}{\sum (y_i - \bar{y})^2} \quad (1)$$

where $\hat{y}_i$ is the predicted value from the AS7265x sensor, y_i is the corresponding LI-COR LI-180 measurement, and $\bar{y}$ is the mean of the reference data.

The root mean square error (RMSE) was used to quantify the average deviation between predicted and reference values. RMSE provides an absolute measure of prediction error and complements R^2 in evaluating model performance (Chicco et al., 2021). The RMSE is calculated as shown in Equation (2).

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (\hat{y}_i - y_i)^2} \quad (2)$$

where n represents the number of observations. In this study, R^2 and RMSE were jointly used to assess calibration accuracy and predictive reliability across wavelengths.

System Implementation

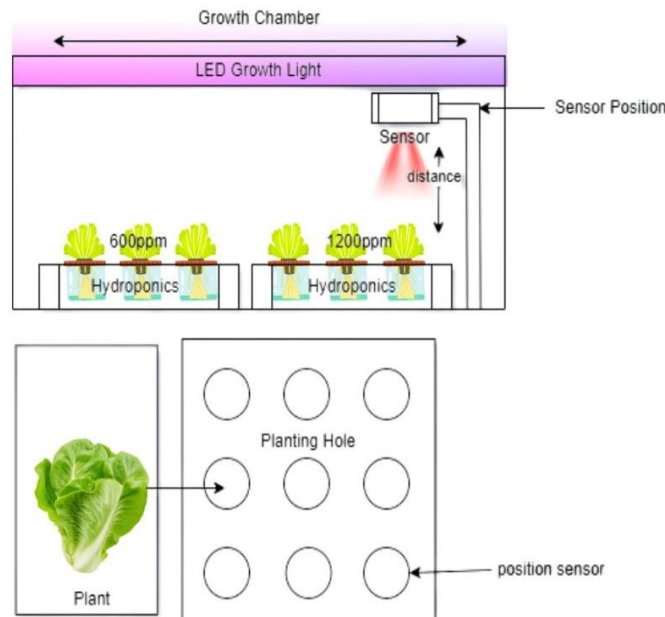


Figure 3. Experimental setup of the monitoring system in a controlled hydroponic environment, including sensor placement and nutrient treatments

The monitoring system was implemented in a controlled hydroponic cultivation setup using lettuce (*Lactuca sativa* L.) as the experimental plant. The spatial arrangement of the growth chamber, sensor position, and hydroponic

system is presented in Figure 3. The sensor was positioned above the plant canopy to capture reflectance signals consistently across all samples.

Lettuce plants at 28 days after planting were observed over a 10-day period, with measurements conducted on day 1, day 5, and day 10. Each measurement consisted of three replications and was performed at three time points (08:00, 14:00, and 18:00 WIB) to minimize temporal variability. The recorded spectral values were averaged to obtain representative reflectance data for each condition.

Two nutrient treatments were applied to evaluate system performance under different plant physiological conditions, namely 600 ppm (pH 5.5–6.5) and 1200 ppm (pH < 5). Plants were grown under controlled environmental conditions, including a constant temperature of 20°C, relative humidity of 80%, and LED lighting operated from 06:00 to 24:00 at 50% intensity. The distance between the sensor and the plant canopy was maintained at 10 cm to ensure consistent measurement geometry. Chlorophyll content was measured using a SPAD meter to provide independent physiological validation.

Spectral Acquisition and Reflectance Conversion

Spectral data were acquired using the AS7265x sensor within the wavelength range of 410–760 nm. The sensor recorded raw spectral responses as digital intensity values corresponding to reflected light at each wavelength. These raw values were subsequently converted into relative reflectance to improve comparability across samples and measurement conditions.

Reflectance values were calculated using white and dark reference calibration, as defined in Equation (3). This approach corrects for sensor dark current and reduces the influence of ambient light variability during measurement. The resulting reflectance values provide a normalized representation of plant spectral response.

$$R(\lambda) = \frac{I_{sample}(\lambda) - I_{dark}(\lambda)}{I_{white}(\lambda) - I_{dark}(\lambda)} \quad (3)$$

where $I_{sample}(\lambda)$ is the intensity measured from the plant sample, $I_{white}(\lambda)$ is the intensity from a white reference surface, and $I_{dark}(\lambda)$ is the dark reference intensity. This calibration procedure improves the consistency and reliability of spectral measurements across different acquisition sessions.

Results and Discussion

Sensor Calibration Performance

Table. 1 Linear regression models for reflectance calibration between the AS7265x sensor and the LI-COR LI-180 reference spectrometer

Wavelength (nm)	Linear regression model ($y = ax + b$)	R ²	RMSE
410	0.8342x – 0.0261	0.9870	0.26965
435	0.8210x – 0.8529	0.9713	1.63401
460	0.8108x – 1.5833	0.9682	2.66863
485	0.8855x – 0.5089	0.9701	2.23594
510	0.8614x – 0.9129	0.9679	3.60679
535	0.8905x + 0.0541	0.9688	5.19772
560	1.5450x + 8.3770	0.9755	4.94921
585	1.2220x + 3.6279	0.9686	3.50987
610	0.8899x + 0.3516	0.9695	3.08239
645	0.9579x + 1.1286	0.9706	2.54638
680	0.8320x + 0.1092	0.9757	1.35128
705	1.0785x + 1.3877	0.9751	1.99535
730	1.0273x + 1.3788	0.9742	2.25126
760	1.0963x + 0.6775	0.9825	0.97584

Linear regression analysis was conducted to quantify the calibration relationship between the AS7265x sensor and the LI-COR LI-180 reference spectrometer across individual wavelengths within the 410–760 nm spectral

range. This approach establishes a functional relationship between sensor output and reference measurements, allowing systematic deviations to be corrected. The resulting calibration models form the basis for evaluating the reliability of the sensor under controlled experimental conditions (Chen & Chen, 2022).

As presented in Table 1, the calibration models exhibit consistently high coefficients of determination (R^2), ranging from 0.9682 to 0.9870 across all wavelengths. These results indicate a strong linear relationship between the AS7265x sensor and the LI-COR LI-180 reference measurements. The consistency of R^2 values across the spectral range suggests that the sensor is capable of capturing reflectance trends with high stability after calibration.

The highest calibration performance is observed at 410 nm and 760 nm, where high R^2 values coincide with relatively low RMSE values. This combination indicates strong agreement and low prediction error at both ends of the spectral range. In contrast, higher RMSE values are observed in the 510–560 nm region, as shown in Table 1, indicating reduced calibration accuracy within the green spectral band.

The increased residual error in the green region is likely associated with the sensitivity of leaf reflectance to physiological variability, particularly chlorophyll concentration and internal leaf structure. Variations in these properties can amplify discrepancies between sensor measurements, especially when using discrete multispectral sensors. In addition, differences in sensor spectral response at specific wavelengths may contribute to the observed deviations.

The regression coefficients further indicate that most slope values are close to unity, reflecting proportional agreement between the AS7265x sensor and the reference instrument. However, deviations from unity are evident at certain wavelengths, such as 560 nm, where the slope exceeds 1.5, indicating wavelength-dependent sensitivity differences. The presence of non-zero intercept values across several wavelengths also confirms the existence of systematic bias, although its magnitude remains relatively limited.

These results demonstrate that the AS7265x sensor provides consistent reflectance measurements after calibration, with performance varying depending on wavelength. The calibration models presented in Table 1 enable the correction of systematic differences and support the use of the sensor for relative spectral analysis in controlled environment applications.

Spectral Response Consistency Between Sensors

The spectral response comparison between the AS7265x sensor and the LI-COR LI-180 reference spectrometer is presented in Figure 4. Both instruments exhibit highly consistent reflectance patterns across the 410–760 nm wavelength range for both nutrient treatments. Characteristic spectral features are clearly observed, including reflectance peaks in the green region (approximately 510–560 nm) and a subsequent decline toward the red region, followed by a slight increase in the red-edge region.

Despite the similarity in spectral shape, the AS7265x sensor consistently produces higher reflectance values than the LI-COR LI-180, particularly within the 435–610 nm range, as shown in Figure 4. This indicates the presence of a systematic offset between the two instruments, which is consistent with the non-zero intercept values obtained from the calibration models. The magnitude of this deviation appears more pronounced under the 600 ppm treatment, suggesting that plant condition may influence the degree of measurement bias between sensors.

The consistency in spectral shape between the two sensors indicates that the AS7265x is capable of capturing relative spectral variations reliably. This is a critical aspect for plant monitoring applications, where the interpretation of spectral patterns is often more relevant than absolute reflectance values. The ability to reproduce similar spectral curves under different treatments demonstrates that the sensor maintains stability in detecting changes in plant optical responses.

As illustrated in Figure 4, distinct differences between the 600 ppm and 1200 ppm treatments are observed, particularly in the green and red-edge regions. These differences are associated with variations in chlorophyll content and leaf structure, which directly affect light absorption and scattering properties. Higher reflectance values under the 1200 ppm treatment indicate improved physiological conditions, likely due to enhanced nutrient availability.

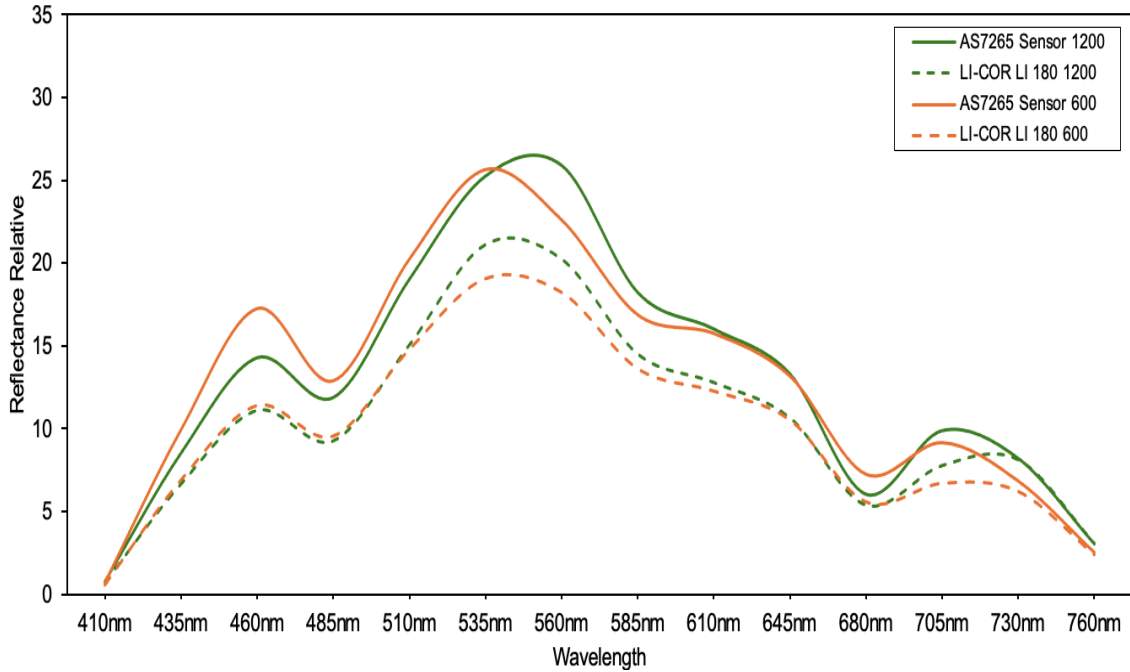


Figure 4. Spectral response comparison between the AS7265x sensor and the LI-COR LI-180 under different nutrient concentrations (600 ppm and 1200 ppm)

The spectral behavior in the red-edge region (approximately 705–730 nm) further supports this interpretation, as this region is highly sensitive to changes in chlorophyll concentration and plant vigor. A shift or enhancement in reflectance within this region is commonly associated with improved plant physiological status. The ability of the AS7265x sensor to capture these variations indicates that it can detect physiologically relevant changes in a non-destructive manner (Ali et al., 2022). These results demonstrate that, although a systematic offset exists, the AS7265x sensor preserves the spectral characteristics observed by the reference instrument. This capability enables its application for relative plant monitoring and comparative analysis under controlled environmental conditions (Sutherland et al., 2024).

System Evaluation Under Different Nutrient Conditions

To evaluate the performance of the monitoring system under different plant conditions, regression analysis was conducted for two nutrient treatments (600 ppm and 1200 ppm). The spectral reflectance curves obtained from both sensors show consistent patterns across all measured wavelengths, indicating that the system is able to capture similar spectral responses under varying nutrient conditions. In addition, the relationship between the AS7265x sensor and the LI-COR LI-180 was examined using linear regression to assess measurement agreement.

The spectral reflectance comparison and regression results are presented in Figure 5. The reflectance curves in Figure 5(a) and 5(c) demonstrate similar spectral shapes between the two instruments, particularly in the green and red-edge regions. Furthermore, the scatter plots in Figure 5(b) and 5(d) indicate a strong linear relationship, confirming that the sensor is capable of tracking the reference measurements under both nutrient treatments.

As presented in Table 2, high coefficients of determination (R^2) were obtained for both treatments, with values of 0.9819 for 600 ppm and 0.9915 for 1200 ppm. These results indicate that the AS7265x sensor maintains a strong linear relationship with the reference instrument under varying nutrient conditions. The slightly higher R^2 observed at 1200 ppm suggests more stable spectral behavior under improved physiological conditions.

The regression coefficients further reveal that the slope values remain below unity for both treatments, indicating that the AS7265x sensor tends to underestimate reflectance magnitude relative to the LI-COR LI-180. At the same time, the positive intercept values indicate the presence of a systematic offset between the two instruments. This behavior is consistent with the deviation from the ideal 1:1 relationship observed in Figure 5(b) and 5(d).

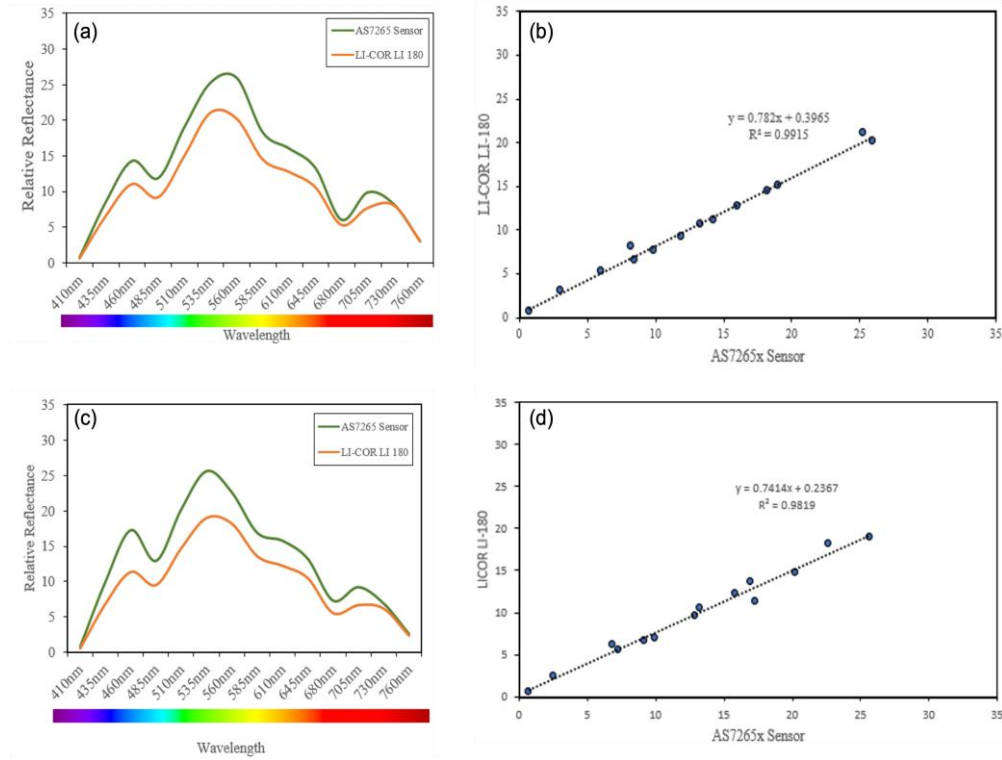


Figure 5. Spectral reflectance and regression analysis under different nutrient concentrations: (a) spectral reflectance at 1200 ppm, (b) regression at 1200 ppm, (c) spectral reflectance at 600 ppm, and (d) regression at 600 ppm across key wavelength regions (435–485 nm, 510–560 nm, and 705–730 nm)

Table 2. Linear regression performance of the AS7265x sensor under different nutrient concentrations

Plant Nutrition	Slope (a)	Intercept (b)	R ²	RMSE
600 ppm	0.7414	0.2367	0.9819	11.17
1200 ppm	0.7820	0.3965	0.9915	11.56

The RMSE values presented in Table 2 are higher compared to the wavelength-specific calibration results, indicating increased prediction error when multiple wavelengths are evaluated simultaneously. This effect is likely caused by cumulative variability across spectral bands, combined with physiological changes in plant samples during the observation period. Factors such as leaf structure, water content, and chlorophyll concentration contribute to this variability. Despite these deviations, both sensors consistently capture key spectral regions associated with plant physiological responses, as shown in Figure 5(a) and 5(c). Prominent features are observed in the blue (460–485 nm), green (510–560 nm), and red-edge (705–730 nm) regions, which are closely related to chlorophyll absorption and leaf structural properties. This consistency indicates that the sensor is capable of detecting meaningful variations in plant condition under different nutrient treatments.

The results demonstrate that the AS7265x sensor is able to follow the spectral response pattern of the reference instrument under varying nutrient conditions, although absolute agreement is not fully achieved. The presence of systematic bias and increased error at aggregated levels highlights the importance of calibration for quantitative applications. The preserved spectral pattern, however, supports its use for relative plant monitoring in controlled environments.

Effect of Nutrient Concentration on Spectral Characteristics

Variations in nutrient concentration resulted in observable differences in plant physiological response, as reflected by SPAD measurements. Plants grown under higher nutrient availability exhibited increased chlorophyll content compared to those under lower nutrient conditions. This difference indicates that nutrient supply directly influences plant physiological status through chlorophyll accumulation. The comparison of average SPAD values under different nutrient concentrations is presented in Figure 6. As shown in the figure, plants grown under 1200 ppm exhibit higher SPAD values than those grown under 600 ppm. This pattern confirms that increased nutrient concentration enhances chlorophyll content, which is a key indicator of plant health and photosynthetic capacity.

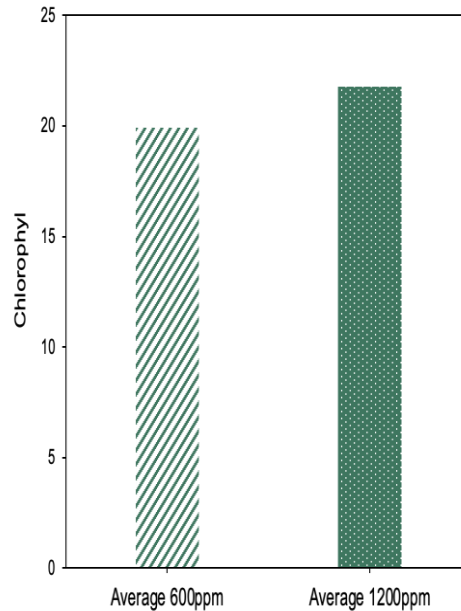


Figure 6. Comparison of average SPAD values under different nutrient concentrations (600 ppm and 1200 ppm), indicating differences in leaf chlorophyll content

The variation in SPAD values is consistent with the spectral reflectance patterns observed in the previous section, particularly in the green (510–560 nm) and red-edge (705–730 nm) regions. These spectral regions are highly sensitive to chlorophyll concentration and nitrogen status, as chlorophyll strongly affects light absorption and internal scattering within leaf tissues. The agreement between SPAD measurements and spectral responses indicates that nutrient-induced changes are reflected in both physiological and optical plant characteristics. Higher nutrient availability promotes chlorophyll synthesis, which increases light absorption in the blue and red regions while modifying reflectance behavior in the green region. In addition, changes in leaf internal structure, including increased cell density and enhanced scattering, influence reflectance in the red-edge region. These combined effects explain the stronger spectral responses observed under the 1200 ppm treatment.

The improved agreement between the AS7265x sensor and the reference instrument under higher nutrient conditions, as discussed in the previous section, suggests that plant physiological stability contributes to more consistent spectral measurements. Plants with higher chlorophyll content tend to produce more stable spectral signals, which reduces variability in sensor readings. This relationship supports the use of spectral sensing for detecting relative differences in plant condition.

The results indicate that nutrient-induced variations in plant physiology can be captured through both SPAD measurements and spectral reflectance patterns. Although the system does not directly quantify biochemical parameters, the consistent relationship between chlorophyll-related indicators and spectral response provides a basis for indirect assessment of plant quality in controlled environments.

Conclusion

This study demonstrates that the AS7265x multispectral sensor provides reliable spectral measurements for plant monitoring in a controlled hydroponic environment after calibration. High linear agreement with the reference spectrometer ($R^2 = 0.9682\text{--}0.9870$) confirms that the sensor can capture reflectance trends consistently across the 410–760 nm range, although wavelength-dependent deviations and systematic offsets remain. The sensor successfully preserved key spectral features, particularly in the green and red-edge regions, which are closely related to chlorophyll dynamics. Variations in nutrient concentration were consistently reflected in both spectral responses and SPAD measurements, indicating that the system is sensitive to physiologically relevant changes in plant condition. These results indicate that the AS7265x sensor is suitable for relative plant monitoring and comparative analysis in controlled environments. However, calibration remains essential for quantitative applications due to residual bias and variability across wavelengths. The integration of spectral sensing with physiological indicators provides a practical approach for improving the reliability of low-cost monitoring systems in precision agriculture.

Recommendations

Future research should focus on improving calibration strategies to reduce wavelength-dependent bias and enhance quantitative accuracy, particularly in the green spectral region where higher residual errors were observed. The integration of advanced calibration methods or machine learning-based correction models may further improve sensor performance across varying plant conditions. Further studies are also recommended to expand validation across different crop types, growth stages, and environmental conditions to assess the generalizability of the system. Incorporating additional physiological indicators beyond SPAD, such as biomass or nutrient content, would strengthen the interpretation of spectral data. In addition, the development of real-time decision-support systems based on VIS–NIR sensing is recommended to enhance practical implementation. Integrating spectral monitoring with automated control systems in controlled environments may improve precision in nutrient management and overall cultivation efficiency.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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Author(s) Information

Arifa Haryani

Universitas Gadjah Mada

Yogyakarta, Indonesia

ORCID iD: <https://orcid.org/0009-0003-6470-5843>

*Contact e-mail: arifaharyani@mail.ugm.ac.id

Andri Prima Nugroho

Universitas Gadjah Mada

Yogyakarta, Indonesia

ORCID iD: <https://orcid.org/0000-0002-5375-2439>

Nazmi Mat Nawi

Universitas Putra Malaysia

43400 UPM serdang, Selangor Malaysia

ORCID iD: <https://orcid.org/0000-0002-5916-5745>

Mohammad Affan Fajar Falah

Universitas Gadjah Mada

Yogyakarta, Indonesia

ORCID iD: <https://orcid.org/0000-0002-1276-218X>

Lilik Sutiarto

Universitas Gadjah Mada

Yogyakarta, Indonesia

ORCID iD: <https://orcid.org/0000-0003-0167-4800>

Ardan Wiratmoko

Universitas Gadjah Mada

Yogyakarta, Indonesia

ORCID iD: <https://orcid.org/0000-0001-9224-5555>

Muhammad Athala Fawwaz Dzaky

Universitas Gadjah Mada

Yogyakarta, Indonesia

ORCID iD: <https://orcid.org/0009-0006-0406-437X>

Samuel Gatot Marseno

Universitas Gadjah Mada

Yogyakarta, Indonesia

ORCID iD: <https://orcid.org/0009-0009-7568-8245>

*Corresponding author(s) contact email

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Optimal Sizing of a Sustainable and Climate Resilient Microgrid System

Adrian L. Rey

Polytechnic University of the Philippines

Harry Alan P. Errasquin

Polytechnic University of the Philippines

Ginno L. Andres

Polytechnic University of the Philippines

Abigail C. Andres

Polytechnic University of the Philippines

Arvin R. De La Cruz

Polytechnic University of the Philippines

Abstract: The research investigates the potential of an off-grid microgrid system powered by renewable energy sources in Barangay Ransang, a remote village in Palawan. The study aims to determine the renewable energy potential, identify the most economical combination of renewable energy sources, and evaluate the financial benefits of the proposed system. The researchers used HOMER software to simulate and optimize the microgrid system, identifying a 2.0 MWp solar PV array, 0.840 MW diesel generators, and a 1.0 MWh battery energy storage system as the optimal solution. This configuration provides 40% renewable fraction and a cost of energy of \$0.287/kWh. The Simplified Planning Tool (SPT) validated the results, confirming the feasibility of the proposed microgrid system. The hybrid power plant's levelized cost of electricity (LCOE) is \$0.287/kWh, significantly cost-saving compared to a diesel-only system with an LCOE of \$0.424/kWh. Implementing this off-grid microgrid system in Barangay Ransang is projected to result in annual savings of \$578,219.10 in Universal Charge on Missionary Electrification (UCME) subsidy, further contributing to the project's economic viability. The findings can serve as a reference for other off-grid electrification projects in the Philippines and beyond, offering potential benefits to remote areas waiting to be electrified.

Keywords: Microgrid system, Optimal sizing, Renewable energy, Hybrid system, Village electrification

Introduction

Barangay Ransang in the Municipality of Rizal is one of the un-electrified villages in the Province of Palawan. It is approximately 230 kilometers from the City of Puerto Princesa and more than 10 kilometers from the town proper of Rizal. Due to its location, the line connection to the existing distribution line is costly and technically impractical. One possible solution for the electrification of Barangay Ransang is the use of off-grid microgrid technology utilizing renewable energy sources. An off-grid microgrid is a standalone system that is not connected to the main grid of electricity. With this technology, the barangay will have its own power generation facility and distribution system to provide electricity within the area. The lack of continuous, affordable, clean, and reliable electricity supply in village affects the residents' living conditions, preventing them from improving their healthcare, education, and livelihood.

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- Selection and peer-review under responsibility of the Organizing Committee of the Conference

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Objectives of the Study

The study aims to determine the viability of installing an off-grid microgrid system utilizing renewable energy sources in Barangay Ransang. The specific objectives of the study are the following:

1. Determine the renewable energy potential of the area.
2. Determine the most economical combination of renewable energy sources for the microgrid system.
3. Determine the financial benefits of the system.

This study is important to ensure a continuous supply of electricity in a clean and reliable manner at an affordable price for the residents. This can also be a reference for other off-grid electrification projects in the country. There are still a lot of remote areas waiting to be electrified, and this study can help the stakeholders in rural electrification conduct their feasibility studies. Distribution line design for the microgrid system is not part of this study. Same with the design of the power generation facility. This study will only determine the most viable renewable energy configuration for the power plant considering its techno-economical aspects. Sizing of the solar PV, diesel generator, and battery backup system is included in the study.

Review of Related Literature

In recent years, the investigation of off-grid hybrid renewable power systems has attracted significant attention from researchers worldwide. Brijesh et al. (2019) conducted a study using microgrid for sustainable development of remote villages. Babayomi et al. (2020) presented the importance of energy efficiency for sustainable renewable microgrids for off-grid electrification. Singh Dhawan and Tamrakar (2022) studied the potential of standalone microgrids as a sustainable option for energy handling. Furthermore, Kumar et al., (2018) suggested a novel methodological framework for the design of a sustainable rural microgrid for developing nations. While Zaman and Razzak (2022) accomplished a sustainable microgrid analysis for Kutubdia Island of Bangladesh.

Researchers further explored the use of microgrid system utilizing different combination of technologies for various applications. Keskamol and Hoonchareon (2015) studied the sizing of battery energy storage system for sustainable energy in a remote area. Habib et al. (2019) accomplished a PV-Wind-Battery based standalone microgrid system with MPPT, (Zaman and Ongsakul, 2022) introduced a hybrid microgrid optimization for smart city planning on Saint Martin's Island in Bangladesh. Mukhopadhyay and Ray (2021) conducted a techno-economic-environment analysis of solar PV smart microgrid for sustainable rural electrification in agriculture community. Bandyopadhyay et al. (2020) also made a techno-economical model based optimal sizing of PV-Battery systems for microgrids. It is evident in the previous researches the importance of a techno-economical analysis in ensuring the optimal and sustainable design of a microgrid system. Santos et al. (2021) presented an integrated optimal sizing and dispatch strategy for microgrids using HOMER Pro. Popescu (2021) also utilized HOMER Pro software in conducting a techno-economic analysis for renewable energy microgrid systems. Islam et al. (2021) optimized a microgrid system for community electrification by using HOMER Pro, similar to Baral et al. (2022) in the design and economic optimization of community load based microgrid system.

Missionary Electrification in the Philippines

The 2030 Agenda for Sustainable Development was adopted by the United Nations Member States in 2015, with 17 Sustainable Development Goals (SDGs) to urge all countries to achieve a more sustainable future for all. Considered crucial to the achievement of most of these goals is SDG 7 - affordable and clean energy access. Energy access is defined as access to electricity and modern cooking, with electricity access considered to be fundamental to poverty eradication, improved health, quality education, economic growth, and inclusive sustainable development. The Philippines aims to achieve 100% electrification at household level in the next few years and the Department of Energy (DOE) has reported that as of December 2016, household electrification rate for the entire country is at 90.65%. The Philippine electrification system is categorized into on-grid and off-grid, where on-grid areas are connected or served by the main transmission backbone of Luzon, Visayas, and Mindanao, serviced by the National Grid Corporation of the Philippines (NGCP); and off-grid areas are electrified by the National Power Corporation Small Power Utilities Group (NPC-SPUG).

Republic Act No. 9136, otherwise known as the Electric Power Industry Reform Act or EPIRA, was enacted in 2001 as overarching legislation to manage electrification in the country and to transition to cleaner sources of energy. Pursuant to Sec. 2 (a) of EPIRA, the government stipulates the acceleration of total electrification of the

country. With this declaration, the NPC-SPUG or its successors-in-interest, distribution utilities (DUs) concerned, and/or qualified third parties (QTPs) are mandated to provide missionary electrification to off-grid areas in the country that are unserved or underserved in terms of electricity access. DOE, through its Implementing Rules and Regulations (IRR) of EPIRA, defines missionary electrification as the provision of basic electricity service in unviable areas or areas within the mandated franchise area of a DU where the extension of the distribution line is not feasible. Missionary electrification has the ultimate goal of bringing the operation in these areas to an acceptable level. By its definition, missionary electrification covers all off-grid areas in the country.

Through DOE's 2016-2030 Philippine Energy Plan, three programs are identified to support off-grid electrification efforts in order to achieve 100% household electrification: (a) household Electrification Program (HEP), which aims to accelerate renewable energy adoption with the use of mature renewable energy technologies (RETs) such as solar photovoltaics (PV) to provide electricity access to off-grid households; (b) mainstreaming of Solar PV through the Access to Sustainable Energy Program (ASEP), where DUs are encouraged to implement solar home systems (SHS) to dispersed households in remote areas; and (c) Qualified Third Party (QTP) Program, allowing qualified third parties to provide electricity access to areas deemed unviable and waived by the DUs. A more recent development in 2022 is the passing of the Philippine Microgrid Systems Act accelerating the development of microgrid systems for rural electrification in the country.

Methodology

A software called HOMER (Hybrid Optimization of Multiple Energy Resources) was used for system optimization. This software is an internationally accepted tool in the simulation of microgrid systems. The techno-economic analysis was conducted using this tool. Simulation results were analyzed, and the most viable power system configuration was recommended. Figure 1 below shows the conceptual framework for the study.

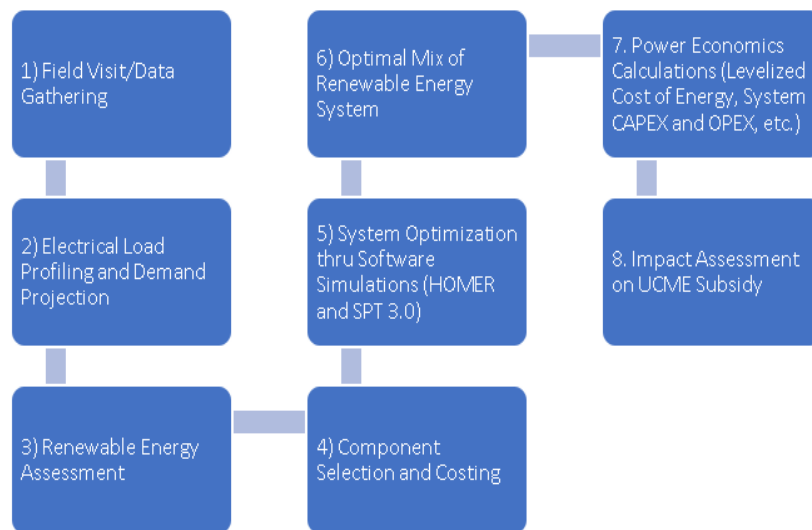


Figure 1. Conceptual framework of the study

The conceptual framework includes the following activities (1) data gathering and actual field surveys to gather not only granular technical and operational/financial data but also get the insights and suggestions of stakeholders (2) electrical load profiling and demand projections to determine the energy consumption of the study area (3) renewable energy assessment to identify the available renewable energy resources for power generation (4) component selection and costing as a major input in system optimization (5) determination of the optimal renewable energy supply mix for the study area by using two different tools a) HOMER Software and b) an Excel-based tool called Simplified Planning Tool (SPT) 3.0 for comparison of results (6) analysis of the calculated optimal supply mix (7) power economics calculations to determine the financial viability of the system, and (8) assessment on the impact of sustainable microgrid to the use of Universal Charge on Missionary Electrification (UCME) subsidy. EPIRA prescribed UCME imposable to all-electric consumers nationwide.

The UCME established the provision of subsidies in areas under missionary electrification so that development and progress could also happen in these areas similar to grid-connected communities. End users under missionary electrification are only required to pay the Subsidized Approved Generation Rate (SAGR) plus any ERC-approved

cost adjustments notwithstanding the higher True Cost Generation Rate (TCGR) of these areas. The difference between TCGR and SAGR is claimed from the UCME Subsidy.

HOMER Simulation

Load profile preparation and renewable energy assessment were done before the HOMER simulation. A detailed evaluation of the electrical load demand of the community and available solar energy resources was separately conducted. This is carried out outside the software, and data is fed for the simulation. The electrical load profile and demand projection for Barangay Ransang were gathered thru an electrical load survey. HOMER first runs an hourly simulation of all possible configurations on different system types. The speed of simulation processing allows for the evaluation of thousands of combinations. This hourly simulation also provides improved accuracy over statistical models that typically evaluate the average monthly performance of a system. The modeling process done by the software involves two key stages: i) technical feasibility; and ii) comparison of life cycle costs. HOMER first tests the capability of each proposed configuration to serve the electric loads in the power grid within a set of constraints set by the modeler. Once the electrical demand is addressed, HOMER calculates the lifecycle cost of the system for each configuration using user-defined factors, such as the load size, reliability requirements, and resource quality. The lifecycle cost or the levelized cost of electricity (LCOE) is computed using the discounted cash flow method, i.e., the net present value of all the costs of installing (CAPEX) and operating (OPEX) the system over the project life.

During HOMER simulations, the projected demand will be subjected to random variabilities to add randomness to the load data to make it more realistic. These random variabilities are day-to-day variability and timestep variability. After the simulation process, the software sorts the feasible results in order of increasing net present value (NPV). This cost is the present value of the capital cost, component replacement, operation and maintenance cost, and fuel costs. The software lists the optimal system configuration for each system type, defined as the one with the least net present value. The goal of the optimization process is to identify the optimal value of each variable. The possible decision variables in the study are the following:

1. The capacity of the solar PV
2. The capacity of the diesel generator sets
3. The capacity of the battery energy storage system
4. The control or applicable system dispatch

The sensitivity analysis in the software then repeats this optimization using user-defined factors, such as diesel fuel price, electrical demand, system reliability requirement, and resource quality.

Software Inputs

Tables 1 to 3 show the technical and financial inputs for the HOMER simulation. These values are based on the actual costs and technical specifications of equipment identified for the project. Cost inputs are not only referring to the equipment itself but also include the cost of the balance of the system to have a complete operational system.

Table 1. Solar PV inputs

Item	Unit	Value
530 Wp, Monocrystalline, Half-cell Module		
Capital cost per kW	\$	1,100
Replacement cost per kW	\$	1,000
O&M cost per kW	\$/year	35
Lifetime	years	25
Derating factor	%	84.8

The replacement cost is lower than the capital cost because some of the system components, like mounting structures, cables, etc., can still be used after the replacement of solar panels. This is also applicable to the replacement cost for diesel generators, batteries, and bi-directional inverter. The minimum load ratio of the diesel generators is at 40% to maintain the good value of specific fuel oil consumption (SFOC). An annual increase of two (2) percent in fuel price is included in the simulation to determine the impact of increasing fuel price on the optimal configuration of the hybrid power plant.

Table 2. Diesel generator inputs

Item	Unit	Value
235 kVA (standby rating), silent type, 60 Hz, 1,800 RPM, 3 Phase, 400 Volts		
Capacity (prime rating)	kW	168
Capital cost per unit	\$	40,000
Replacement cost per unit	\$	30,000
O&M cost per unit	\$/RH	2
Fuel price	\$/L	0.9
Minimum load ratio	%	40
Lifetime	hrs	15,000
Minimum Runtime	minutes	60
Fuel curve		
100% loading	L/hr	44
75% loading	L/hr	33
50% loading	L/hr	23
25% loading	L/hr	14

Table 3. Battery inputs

Item	Unit	Value
Lithium Iron Phosphate (LFP), 0.5 C-rate		
Capital cost per MWh	\$	700,000
Replacement cost per MWh	\$	650,000
O&M cost per MWh	\$/year	5,000
Lifetime	years	15
Throughput	kWh	3,000,000
Voltage	V	768
Minimum State of Charge	%	10

Load Profile

Table 4. Projected load profile

Time	Demand (kW)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	407	527	376	470	537	525	389	373	445	482	348	459
1	398	515	368	460	524	513	380	364	435	471	340	448
2	389	503	359	449	512	502	371	356	425	460	332	438
3	380	491	351	438	500	490	362	347	414	449	325	427
4	366	473	338	422	482	472	349	335	399	433	313	412
5	370	479	342	428	488	478	354	339	404	438	317	417
6	338	437	312	390	445	436	323	309	369	400	289	380
7	236	305	218	273	311	304	225	216	258	280	202	266
8	232	299	214	267	305	299	221	212	253	274	198	261
9	273	353	252	315	360	352	261	250	298	323	234	307
10	292	377	269	337	384	376	278	267	318	345	249	328
11	296	383	274	342	390	382	283	271	323	351	253	334
12	296	383	274	342	390	382	283	271	323	351	253	334
13	292	377	269	337	384	376	278	267	318	345	249	328
14	287	371	265	331	378	370	274	263	313	340	245	323
15	287	371	265	331	378	370	274	263	313	340	245	323
16	292	377	269	337	384	376	278	267	318	345	249	328
17	296	383	274	342	390	382	283	271	323	351	253	334
18	324	419	299	374	427	418	309	296	354	384	277	365
19	435	562	402	502	573	561	415	398	475	515	372	490
20	449	580	415	518	591	579	429	411	490	532	384	505
21	463	598	428	534	610	597	442	424	505	548	396	521
22	458	592	423	529	604	591	438	419	500	543	392	516
23	435	562	402	502	573	561	415	398	475	515	372	490

Table 4 presents the projected hourly load profile of the community considering the seasonality of demand in the area. Random variabilities are added to these values during the HOMER simulation to reflect the actual situation at the site. A 2.5 percent annual increase in demand is considered in the simulation to determine the effect of demand increase in the operation of the hybrid power plant.

Solar Resource

The monthly average solar global horizontal irradiance data used in the simulation is from the database of NASA. The annual average data for the site is $5.68 \text{ kWh/m}^2/\text{day}$. The monthly values are presented in Table 5.

Table 5. Daily radiation and clearness index

Month	Clearness Index	Daily Radiation ($\text{kWh/m}^2/\text{day}$)
January	0.554	5.28
February	0.567	5.69
March	0.595	6.2
April	0.626	6.5
May	0.596	5.99
June	0.549	5.38
July	0.553	5.46
August	0.555	5.65
September	0.57	5.89
October	0.542	5.47
November	0.561	5.39
December	0.56	5.23

The clearness index is a measure of the clearness of the atmosphere. It is the fraction of the solar radiation transmitted through the atmosphere to strike the surface of the Earth. It is a dimensionless number between 0 and 1, defined as the surface radiation divided by the extraterrestrial radiation. The clearness index has a high value under clear, sunny conditions and a low value under cloudy conditions.

Results and Discussions

Based on the techno-economic analysis using HOMER software, a system with a capacity of 2.0 MWp solar PV, 0.840 MW (5 x 168 kW) diesel generators, and 1.0 MWh BESS is capable of supplying the demand at a renewable fraction of 40%, as shown in Table 6. All system configurations are in load following dispatch strategy.

Table 6. Simulation results

Solar PV (kW)	DG1 (kW)	DG2 (kW)	DG3 (kW)	DG4 (kW)	DG5 (kW)	DG6 (kW)	BESS (MWh)	COE (\$/kWh)	RE Frac (%)
2000	168	168	168	168	168		1	0.287	40
2000	168	168	168	168	168	168	1	0.289	40
2200	168	168	168	168	168		1	0.291	41
2200	168	168	168	168	168	168	1	0.293	41
2400	168	168	168	168	168		1	0.295	42
2400	168	168	168	168	168	168	1	0.298	42

The resulting cost of energy for the selected system is \$0.287 per kWh. The cost of energy is the true cost of generation rate that the electric consumers will pay for electricity use. To validate the results, another tool was used using the same technical and financial inputs. Table 7 shows the simulation results from the Simplified Planning Tool (SPT). The Reiner Lemoine Institute (RLI), under the EU ASEP technical assistance, has developed SPT for simulating typical off-grid power supply configurations. The tool allows for least-cost analytical assessments based on the levelized cost of electricity, similar to HOMER software.

The results are not exactly the same as HOMER, but the values are close enough to validate the results. Table 8 shows the cost summary in net present value from HOMER. Solar PV has the highest capital cost, but diesel generators will have the highest net present value due to their high fuel expenses.

Table 7. Simulation results from SPT

Parameter	Value	Unit
Load consumption (+losses)	4,220,577.40	kWh/year
System installed PV capacity	2,000.00	kW
Installed battery capacity	1,000.00	kWh
Installed diesel capacity	840	kW
PV output	2,971,100.00	kWh/year
Battery output	659,531.50	kWh/year
Diesel generator output	2,455,260.90	kWh/year
Fuel consumption	614,372.20	liter/year
LCOE	13.06	PHP/kWh
RE-share	41%	in percent
Unmet load	0	kWh/year

Table 8. Cost summary of the system

Cost Summary (Net Present)	System	Solar PV	DG	Batteries	Bi-directional Inverter
Capital	\$3,190,000	\$2,200,000	\$200,000	\$700,000	\$90,000
Replacement	\$913,103	\$0.00	\$241,946	\$637,279	\$33,878
O&M	\$1,194,482	\$810,619	\$297,011	\$57,901	\$28,951
Fuel	\$5,050,630	\$0.00	\$5,050,630	\$0.00	\$0.00
Salvage	(\$289,324)	(\$127,523)	(\$18,185)	(\$143,616)	\$0.00
Total	\$10,058,891	\$2,883,096	\$5,771,402	\$1,251,565	\$152,829

Table 9. DG operation parameters

Description	Unit	DG 1	DG 2	DG 3	DG 4	DG 5
Hours of operation	hours/yr	5,168	4,238	2,977	438	3
Number of starts	starts/yr	376	377	547	231	3
Operational life	yr	2.9	3.54	5.04	34.2	5,000
						0.013
Capacity factor	%	54.7	44.3	23.9	2.52	7
Fixed generation cost	\$/hr	7.15	7.15	7.15	7.15	7.15
Marginal generation cost	\$/kWh	0.214	0.214	0.214	0.214	0.214
			651,99	351,81		
Electrical production	kWh/yr	805,662	6	3	37,138	202
Mean electrical output	kW	156	154	118	84.8	67.2
Minimum electrical output	kW	67.2	67.2	67.2	67.2	67.2
Maximum electrical output	kW	168	168	168	168	67.2
			170,07			
Fuel consumption	L/yr	209,912	0	94,184	10,375	58.5
Specific fuel consumption	L/kWh	0.26	0.26	0.27	0.28	0.29
		2,065,53	1,673,4	926,77	102,09	
Fuel energy input	kWh/yr	6	91	5	4	576
Mean electrical efficiency	%	39	39	38	36	35

Tables 9 to 11 present the operation parameters of the hybrid power system in its first year of operation. The average battery autonomy of the upgraded system is 2.44 hours. When fully charged, the BESS can continuously supply power to the demand for up to 2.44 hours without solar PV and diesel generators. This is important when the production of solar panels is low. The storage bank autonomy is the ratio of the storage bank size to the electric load. HOMER calculates the storage bank autonomy using the following equation:

$$A_{batt} = \frac{N_{batt} V_{nom} Q_{nom} \left(1 - \frac{q_{min}}{100}\right) (24 \text{ h/d})}{L_{prim,ave} (1000 \text{ Wh/kWh})} \quad (\text{Eq. 1})$$

With: N_{batt} :number of batteries in the storage bank, V_{nom} :nominal voltage of single storage (V), Q_{nom} :nominal capacity of single storage (Ah), q_{min} : minimum state of charge of the storage bank (%), $L_{prim,ave}$: average primary load (kWh/d)

Diesel Generator 5 is expected to operate at a very minimal time per year. This unit also serves as a contingency reserve when one of the other units will need repair or maintenance. According to the definition from the Philippine Grid Code of 2001, a contingency reserve is the generating capacity intended to take care of the loss of the largest synchronized generating unit or the power import from a single grid interconnection, whichever is larger.

Table 10. Solar PV operation parameters

Description	Value	Unit
Rated capacity	2,000	kW
Mean output	359	kW
Mean output	8,620	kWh/d
Capacity factor	18	%
Total production	3,146,231	kWh/yr
Minimum output	0	kW
Maximum output	1,667	kW
PV penetration	95.4	%
Hours of operation	4,380	hours/yr
Levelized cost	0.0791	\$/kWh

In the first year of operation, around 33% of the energy produced from the solar panels is not utilized, but this value will be reduced to 18.5% on the 20th year of operation. There is excess energy because of the low demand when solar production is high. The demand in the area is primarily residential loads, with the peak happening during night time. The excess energy during the day can still be utilized for solar water pumping and other similar applications.

HOMER uses Equation 2 to calculate the output of the PV array:

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\overline{G}_T}{\overline{G}_{T,STC}} \right) \left[1 + \alpha_P (T_c - T_{c,STC}) \right] \quad (\text{Eq. 2})$$

With: $\overline{P}_{PV}$: the rated capacity of the PV array, meaning its power output under standard test conditions (kW), f_{PV} : the PV derating factor (%), $\overline{G}_T$: the solar radiation incident on the PV array in the current time step (kW/m²), $\overline{G}_{T,STC}$: the incident radiation at standard test conditions (1 kW/m²), α_P : the temperature coefficient of power (%/°C), T_c : the PV cell temperature in the current time step (°C)

$T_{c,STC}$: the PV cell temperature under standard test conditions (25°C)

Table 11. Battery operation parameters

Description	Value	Unit
Autonomy	3.06	hr
Annual throughput	346,043	kWh/yr
Energy in	363,759	kWh/yr
Energy out	328,286	kWh/yr
Average energy cost	0	\$/kWh
Battery wear cost	0.228	\$/kWh
Losses	36,425	kWh/yr
Storage depletion	951	kWh/yr

The average energy cost of the battery in the table is zero. According to the definition of a hybrid system in Article 1.1, PEC Part 1, 2017 Edition: "...Energy storage systems such as batteries, flywheels, or superconducting magnetic storage equipment do not constitute a power source...". The energy cost will be attributed to the power source responsible for the charging. In this case, all energy cost is applied to the solar PV because the system dispatch is load-following. The diesel generators will never charge the batteries. With the true cost of power generation for a diesel only microgrid system at \$0.424/kWh, the proposed system utilizing the available renewable energy sources will have a savings of \$0.137/kWh. This is equivalent to an annual savings of \$578,219.10 in UCME subsidy for the electrification of the community.

Summary and Conclusion

The lack of continuous, affordable, clean, and reliable electricity supply in Barangay Ransang affects the residents' living conditions, preventing them from improving their healthcare, education, and livelihood. This study aims to determine the viability of installing an off-grid microgrid system utilizing renewable energy sources in the village. Based on the techno-economic analysis using HOMER software, a system with a capacity of 2.0 MWp solar PV, 0.840 MW (5 x 168 kW) diesel generators, and 1.0 MWh BESS is capable of supplying the demand at a renewable fraction of 40%. All system configurations are in load following dispatch strategy.

The results were validated with another tool using the same technical and financial inputs. The Reiner Lemoine Institute (RLI), under the EU ASEP technical assistance, has developed SPT for simulating typical off-grid power supply configurations. The tool allows for least-cost analytical assessments based on the levelized cost of electricity, similar to HOMER software. An annual savings of \$578,219.10 in UCME subsidy was calculated as a result of the use of renewable energy resources in the microgrid system.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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Author(s) Information

Adrian L. Rey

Polytechnic University of the Philippines
A. Mabini Campus, Anonas Street, Sta. Mesa, Manila,
1016 Metro Manila, Philippines.
Contact e-mail: engr.adrianrey@gmail.com
ORCID iD: <https://orcid.org/0009-0004-0993-742X>

Harry Alan P. Errasquin

Polytechnic University of the Philippines
A. Mabini Campus, Anonas Street, Sta. Mesa, Manila,
1016 Metro Manila, Philippines.
ORCID iD: <https://orcid.org/0009-0008-3779-2853>

Ginno L. Andres

Polytechnic University of the Philippines
A. Mabini Campus, Anonas Street, Sta. Mesa, Manila,
1016 Metro Manila, Philippines.
ORCID iD: <https://orcid.org/0009-0002-9491-5406>

Abigail C. Andres

Polytechnic University of the Philippines
A. Mabini Campus, Anonas Street, Sta. Mesa, Manila,
1016 Metro Manila, Philippines.
ORCID iD: <https://orcid.org/0000-0002-4818-9784>

Arvin R. De La Cruz

Polytechnic University of the Philippines
A. Mabini Campus, Anonas Street, Sta. Mesa, Manila, 1016
Metro Manila, Philippines.
ORCID iD: <https://orcid.org/0000-0001-7325-5301>

*Corresponding author(s) contact email

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A Comparative Study of Metaheuristics on Raspberry Pi 5: Results to Guide Optimization on Constrained Edge Devices

Ziadan Qowi

Bandung Institute of Technology

Akhdan Musyaffa Firdaus

Bandung Institute of Technology

Hari Purnama

Bandung Institute of Technology

Abstract: This study investigates the efficiency of five metaheuristic algorithms, namely Differential Evolution (DE), Genetic Algorithm (GA), Grey Wolf Optimizer (GWO), Harmony Search (HS), and Particle Swarm Optimization (PSO), when deployed on a Raspberry Pi 5 edge device. The evaluation focuses on both optimization quality and computational cost, using four standard benchmark functions that represent a range of landscape characteristics: Sphere, Rosenbrock, Rastrigin, and Ackley. Each function is tested at dimensions 10, 30, and 50 to probe scalability. In addition to objective values, the experiments collect per-iteration processor usage and memory (RAM) to provide a practical view of runtime overhead under constrained resources. Among the five candidates, GWO consistently delivers the fastest or near-fastest convergence while keeping variability tight. Its trajectories show smooth descent across functions and dimensions, paired with comparatively modest CPU and RAM footprints. PSO typically ranks second in speed with stable dynamics, though brief CPU spikes often appear at early iterations as swarms synchronize. DE demonstrates resilience on rugged functions but generally requires more iterations to close the final gap. GA and HS can reach competitive objective values on some settings, yet they display wider dispersion and higher overhead at larger dimensions, which reduces their suitability for small devices. Overall, the evidence indicates that GWO is the most efficient choice for edge deployment on Raspberry Pi 5, striking a favorable balance between convergence speed, stability, and resource usage. PSO is a strong alternative when slightly higher processor activity is acceptable. These findings support the adoption of lightweight, variance-stable metaheuristics for edge optimization workloads where CPU and memory budgets are tight.

Keywords: Benchmark, Computation, Edge computing, Metaheuristic, Raspberry Pi 5

Introduction

Metaheuristic algorithms such as Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Differential Evolution (DE), Grey Wolf Optimizer (GWO), and Harmony Search (HS) are powerful tools for solving complex optimization problems across engineering and computing domains. Traditionally, these algorithms have been applied on desktop or cloud platforms with ample resource. However, the rise of edge computing and Internet of Things (IoT) has spurred interest in deploying metaheuristics on resource-constrained devices. Embedding optimization intelligence directly on these edge devices can enable on-site decision-making with reduced latency and improved privacy (no cloud dependence) (Khalfi et al., 2023). For instance, tuning control parameters or scheduling tasks on-device via a metaheuristic allows an autonomous system to adapt in real-time without constant cloud communication (Latip et al., 2024). This is a strong motivation for porting metaheuristic methods to constrained hardware can run such algorithms when they are carefully adapted. An 8-bit AVR microcontroller (2 KB RAM) was shown to be capable of executing a Genetic Algorithm (GA) for practical

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tasks, given an implementation optimized for memory and efficiency (Da S. Medeiros et al., 2020). This suggests that metaheuristics, despite their iterative and population-based nature, can be made to fit on tiny edge devices through algorithmic refinements.

Deploying metaheuristics on edge platforms comes with significant challenges. Computational power is limited, for example, a Raspberry Pi 5's CPU cannot match the speed of desktop processor, and a microcontroller is orders of magnitude slower. As a result, algorithms may run an order of magnitude longer to reach a solution. In one performance study, a swarm algorithm was observed to run over ten times slower on a smartphone and Raspberry Pi than on a PC, attributed to lower clock speeds and absent CPU parallelism (Fister et al., 2013). This slowdown is worrisome for time-sensitive applications, and it underscores that naive deployments of standard metaheuristics on edge hardware can be impractically slow. Memory constraints further complicate matters, many metaheuristics maintain a population of candidate solutions, which can consume considerable RAM. In one case, implementing a GA with a modest population of 128 on an ATmega328P (2 KB RAM) consumed about 80% of available memory, leaving virtually no room for other processes (Khalfi et al., 2023). Such tight memory budgets force developers to use smaller population sizes or more compact solution representations. Additionally, edge devices are often energy-constrained. Lengthy or CPU-intensive metaheuristic runs can drain batteries quickly or even heat up the processor to throttling levels. A recent benchmark showed that the Raspberry Pi 5 under load draws 8W and can reach 80°C without active cooling (Minott et al., 2025). Thus, energy efficiency is paramount, an algorithm that converges in fewer iterations or uses simpler operations will prolong device uptime. In summary, limited CPU performance, small memory, and finite energy are fundamental constraints that demand more efficient metaheuristic designs for edge computing. Algorithms need to do more with less, avoiding wasteful computations and memory overhead. Unlike prior studies that focused on earlier Raspberry Pi models or general embedded platforms, this work provides a device-specific benchmark for the Raspberry Pi 5, analyzing not only convergence speed and accuracy but also per-iteration CPU and memory usage under controlled, resource-constrained conditions. This offers practical insights for deploying metaheuristics on modern edge devices where thermal, power, and memory constraints are critical.

Related Works

Despite these challenges, there is growing literature on applying and benchmarking metaheuristics in embedded and edge contexts. Researchers have begun to tailor algorithms or create new variants explicitly for low-power hardware. As an illustration, a two-level PSO variant was designed for embedded deployment, specifically to address a scheduling problem implemented on an STM32 microcontroller and Raspberry Pi B+ hardware (Zarrouk et al., 2022). By restructuring PSO into hierarchical levels and asynchronous updates, they achieved 10-70% reductions in CPU time compared to a standard approach, depending on the desired trade-off in solution quality. This kind of improvement directly translates to energy savings and faster response on the device. For solar panel optimization, a fully embedded implementation of the novel Horse Herd Optimization (HHO) metaheuristic was presented, operating solely on a resource-constrained Raspberry Pi Pico for real-time maximum power point tracking (Punitha et al., 2024). Their implementation leveraged the low complexity of HHO and a custom buck-boost controller to reliably track the optimal power point under changing sunlight, all in real-time on a microcontroller. This practical deployment highlights that advanced optimization can live at the network edge, managing hardware in site. There have also been comparative benchmarking studies. A 2019 experiment integrated several evolutionary and swarm algorithms on three different Raspberry Pi models to evaluate performance across standard mathematical benchmarks (Fister et al., 2019). The results confirmed that execution time grows significantly on weaker hardware, reinforcing the need for algorithmic adjustments or lighter alternatives. Similarly, in tests of multi-objective metaheuristics, a multi-objective GA was successfully deployed on a low-end STM32F microcontroller, proving the feasibility of running complex optimizers on bare-metal hardware through careful engineering (Henriquede Oliveira Santos et al., 2018). In some cases, researchers explore specialized hardware, e.g. FPGA-based accelerators for Harmony Search or other algorithms, to offload computations (Khalfi et al., 2023). While such hardware acceleration can be effective, it is not always available or cost-effective for every edge deployment. Thus, a significant thread of recent work focuses on lightweight or memory saving metaheuristics.

For edge computing applications, the convergence speed of an optimization algorithm is often as critical as its final solution quality. Many edge scenarios require that a good solution be found within strict time limits. If a metaheuristic takes too long to converge on limited hardware, the solution might arrive too late to be useful. Moreover, prolonged run times mean higher energy consumption. A recent systematic review of edge task offloading strategies noted that many solutions based on conventional metaheuristics suffer from poor

convergence speed and high computational cost, limiting their practicality for real-time use (Latip et al., 2024). Slow convergence not only delays decisions but can also trap algorithms in suboptimal regions of the search space. In edge environments, this often manifests as algorithms getting stuck in local optima because they iterate too slowly to navigate the landscape. Stability and reliability of convergence are also paramount. An edge-deployed optimizer should exhibit consistent performance. For example, in the context of solar energy optimization on a microcontroller, traditional algorithms either oscillated around the optimum or took too long to settle, prompting the need for a fast, stable MPPT algorithm (Punitha et al., 2024). In general, an ideal metaheuristic for edge use should balance exploration and exploitation such that it converges to a near-optimal solution swiftly and does so reliably run after run. Some newer algorithms are explicitly designed with this in mind. The GWO, for instance, has gained popularity in edge computing studies due to its simplicity and small number of control parameters, which tend to facilitate faster, more stable convergence in practice. Similarly, variants of PSO and DE have been proposed that incorporate adaptive mechanisms to speed up convergence without sacrificing solution quality (Latip et al., 2024). Ensuring convergence stability is crucial because edge devices often cannot afford extensive re-runs or tuning. Thus, this study pays special attention to both the speed at which each metaheuristic converges on the Raspberry Pi 5 and the stability of the results, recognizing these factors as key enablers for real-time edge deployment.

Method

Experimental Platform

All experiments were conducted on a Raspberry Pi 5 single-board computer, representing a resource-constrained edge device. The Raspberry Pi 5 features a Broadcom BCM2712 system-on-chip with a quad-core 64-bit Arm CortexA76 CPU at 2.4GHz, offering roughly 2-3x the performance of its predecessor. Our model was equipped with 8GB of LPDDR4X-4267 SDRAM, although Raspberry Pi 5 supports up to 16GB RAM. The device ran a 64-bit Linux-based Raspberry Pi OS with Python 3.13 (64-bit) as the runtime environment. All algorithm implementations were executed under identical software conditions, with no other user applications running, to ensure fair use of the CPU and memory. We leveraged the psutil library to monitor system metrics. The experiments were restricted to a single CPU core per run to avoid confounding effects of multi-threading on CPU usage measurements. This hardware and software setup emulates an edge computing scenario where computational resources are limited, making it a suitable testbed for evaluating the efficiency of metaheuristics on low-power devices.

Metaheuristic Algorithms and Parameter Settings

We evaluated five population-based metaheuristic algorithms: Differential Evolution (DE), Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Grey Wolf Optimizer (GWO), and Harmony Search (HS). These algorithms were chosen for their diverse search strategies and widespread use in continuous optimization. Each algorithm was implemented in Python from scratch to ensure a consistent coding style and comparable overhead. All algorithms were configured with a population size of 30 and run for 200 iterations per trial, reflecting common practice in benchmark studies. Other algorithm-specific parameters were set to standard values from literature, e.g. DE mutation factor $F = 0.5$ and crossover rate $CR = 0.95$; GA using binary tournament selection, single-point crossover with 0.8 probability, and bit-flip mutation with 0.1 probability for binary-encoded solutions or analogous Gaussian mutation for real-valued; PSO inertia weight $w = 0.75$ with cognitive and social coefficients $c1 = c2 = 1.5$; HS harmony memory size equal to population, harmony memory considering rate HMCR=0.9, pitch adjusting rate PAR=0.3). all algorithms operate on real-valued solution vectors of dimension d and were minimizing the objective function. All five algorithms were thus run under uniform population size and iteration count, ensuring each performs the same number of objective evaluations (6,000 evaluations per run). The random number generator was seeded differently for each of the 30 runs but consistently across algorithms for fairness. No algorithm specific parallelization or GPU acceleration was used. All computations ran on the Raspberry Pi 5's CPU to reflect true runtime performance on that device.

Benchmark Functions and Problem Dimensions

To assess performance comprehensively, we selected four well known continuous benchmark functions from global optimization literature: Sphere, Rosenbrock, Rastrigin, and Ackley functions. Each of these test functions poses distinct challenges to optimization algorithms, enabling evaluation of algorithm behavior under different

landscape characteristics. The functions were evaluated in three dimensionalities (10, 30, and 50) to examine scalability of the algorithms as problem size increases.

Experimental Procedure

We adopted a rigorous experimental protocol to ensure reliable and statistically meaningful comparisons. Each algorithm was run 30 independent times on each combination of benchmark function and dimensionality (totaling $5 \text{ algorithms} \times 4 \text{ functions} \times 3 \text{ dimensions} \times 30 \text{ runs} = 1800 \text{ runs}$). A full factorial design was thus employed, where we collected performance metrics for every algorithm-problem-dimension tuple. The 30 runs were used to account for stochastic variability and to enable statistical analysis. On each run, the algorithm was initialized with a new random population. We used distinct random seeds for each run but the same sequence of 30 seeds across all algorithms for a given problem and dimension. All runs were executed in a controlled manner on Raspberry Pi 5, one at a time, to avoid resource contention. Before each run, the system was allowed to cool down and idle to ensure consistent starting conditions. We also pinned the process to a specific CPU core to avoid migration overhead between cores and ensured the CPU governor was set to performance to eliminate variability due to dynamic frequency scaling. These precautions help in obtaining stable measurements of execution time and CPU usage for each run. During each run, we measured three types of performance data: (1) the algorithm's convergence behavior, (2) the CPU utilization (%) of the process over time, and (3) the memory usage of the process. To capture convergence, at the end of each iteration we recorded the current best objective value found by the algorithm. This yields a convergence trace of 200 data points for each run, showing how quickly and how well the algorithm approaches the optimum. For CPU and memory, we leveraged psutil calls inserted into the code. Specifically, at each iteration, we sampled the CPU utilization of the Python process and the memory usage in terms of Resident Set Size (RSS) in bytes. These per-iteration samples allow analysis of how resource usage varies as the algorithm progresses. We found that CPU usage readings stabilized after a few initial iterations and the oscillated around a characteristic load for each algorithm. Memory usage generally increased initially and plateaued, reflecting allocation of population structures.

Results and Discussion

In this section, we compare the performance of five metaheuristic algorithms (DE, GA, GWO, HS, and PSO) on four benchmark functions (Sphere, Rosenbrock, Rastrigin, Ackley) at problem dimensions (D) of 10, 30, and 50. All experiments were conducted on a Raspberry Pi 5 to evaluate both optimization effectiveness and computational efficiency in a resource-constrained environment.

Sphere Function Optimization Performance

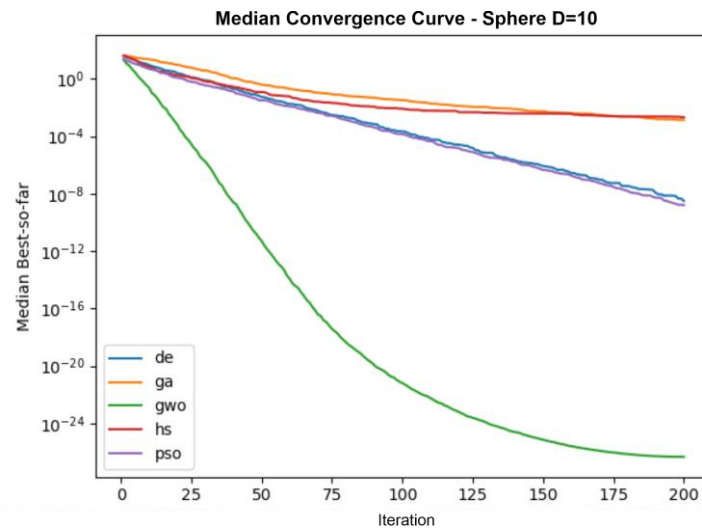


Figure 1. Median convergence curves of optimization algorithms on the Sphere benchmark function in 10 dimensions.

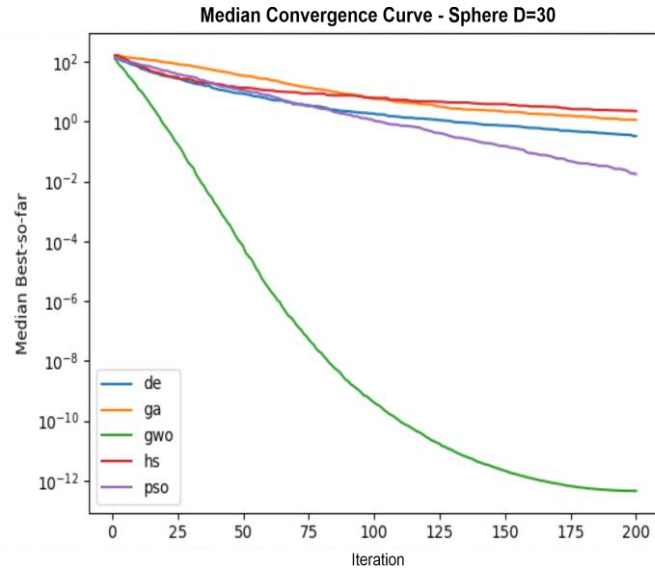


Figure 2. Median convergence curves of optimization algorithms on the Sphere benchmark function in 30 dimensions.

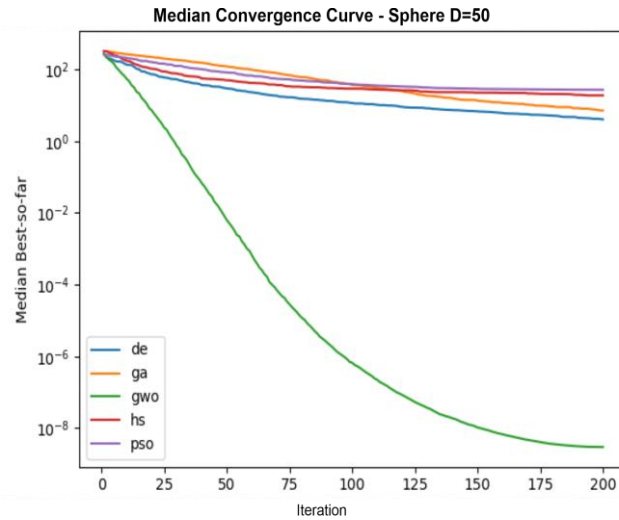


Figure 3. Median convergence curves of optimization algorithms on the Sphere benchmark function in 50 dimensions.

In these unimodal Sphere tests, all algorithms eventually converged toward zero error, but with clear differences in speed and final accuracy. At the lowest dimension, every method reached near-optimal fitness values by 200 iterations. Differential Evolution (DE), Particle Swarm Optimization (PSO), and Grey Wolf Optimizer (GWO) exhibited the fastest reductions in error, rapidly approaching machine precision. In the contrast, the Genetic Algorithm converged more slowly and to a slightly higher median error plateau, indicating some residual error even in this simple landscape. The Harmony Search (HS) showed intermediate behavior, converging adequately but not as quickly as DE/PSO/GWO. As problem dimension increased to D=30 and 50, convergence on Sphere remained robust for the most competitive algorithms, whereas GA and HS struggled further. GWO maintained the best performance, still driving the median error down to 10^{-12} at D=30 and 10^{-8} at D=50. DE and PSO also scaled well. For example, at D=50 their median final errors remained on the order of $10^{-3} - 10^{-4}$, reflecting only a modest degradation in accuracy compared to lower dimensions. HS and GA, however, showed more pronounced performance loss. By D=50, GA plateaued around a median error of order 100, and HS around 10^{-1} , far above the near-zero values of GWO. This indicates that GA and HS often required more iterations to further reduce error or got trapped in longer stagnant phases in higher dimensions. In terms of stability, the Sphere results were consistent across runs for the top algorithms (GWO, DE, and PSO) reliably found very low-error solutions with little variability. GA's outcomes were less stable, with some runs only partially optimizing, and greater run-to-run variance in final fitness. Overall, Sphere benchmarks confirm that DE, PSO, and especially GWO attain rapid and stable convergence even as dimension grows, whereas GA and HS converge slower and less completely as problem size increases.

Rosenbrock Function Optimization Performance

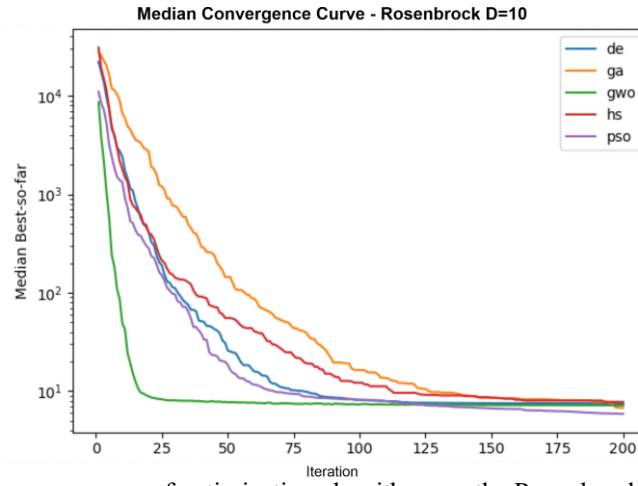


Figure 4. Median convergence curves of optimization algorithms on the Rosenbrock benchmark function in 10 dimensions.

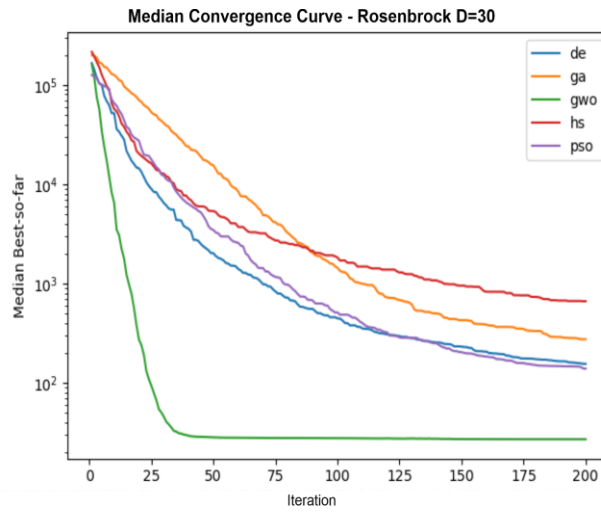


Figure 5. Median convergence curves of optimization algorithms on the Rosenbrock benchmark function in 30 dimensions.

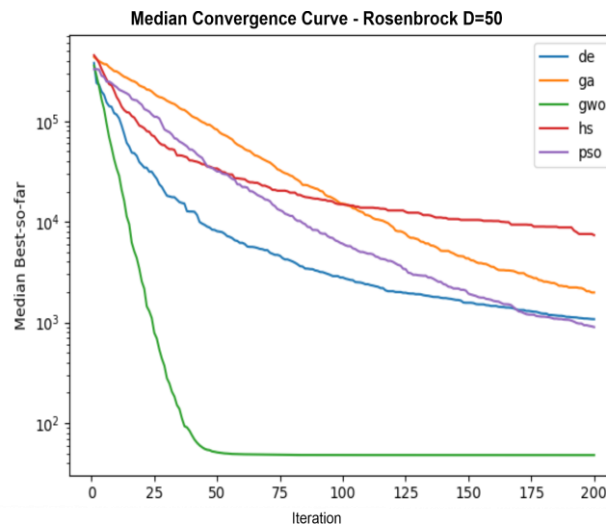


Figure 6. Median convergence curves of optimization algorithms on the Rosenbrock benchmark function in 50 dimensions.

The Rosenbrock function is a difficult, narrow-valley landscape, and the result reflect its challenge. All algorithms were able to reduce the error by several orders of magnitude from their initial values, but only GWO consistently came closest to the optimum. At $D=10$, GWO achieved the lowest median final error, converging to near the bottom of Rosenbrock's valley within the first few dozen iterations. DE, PSO, and HS also converged to the low tens by the end of the run, albeit more slowly and with slightly higher final errors. GA performed noticeably worse in both speed and final accuracy, its error reduction was more gradual, and by 200 iterations GA's median fitness remained around the high tens. This indicates that even in 10 dimensions, GA often struggled with Rosenbrock's ridge structure, whereas GWO navigated it effectively. Increasing the dimension to 30 and 50 exacerbated the performance gaps on Rosenbrock. GWO remained the top performer, scaling gracefully with dimension, for instance, at $D=30$ its median final error was on the order of 10^2 and only slightly higher at $D=50$. In contrast, all other methods showed significantly larger errors in higher dimensions. By the end of 200 iterations at $D=30$, DE and PSO reached median errors on the order of $10^2 - 10^3$, while HS and GA lagged further behind. This trend persisted at $D=50$, DE and PSO attained final medians around 10^3 , whereas GA and HS plateaued in the 10^3 range, an order of magnitude worse than GWO's result. Notably, GA's median error at $D=50$ was about 10^3 and HS's was 10^3 , reflecting that many runs failed to approach the optimum closely in the allotted iterations. Convergence speed on Rosenbrock was fastest for GWO, the green curve in the convergence plots drops steeply in the first 20–30 iterations and flattens near the optimum region. DE and PSO showed moderate convergence speeds, steadily decreasing error but leveling off at higher plateaus, while GA and HS were slower, with GA in particular improving at a glacial pace early on. In terms of stability, GWO again proved reliable: its runs consistently found good solutions with relatively low scatter. The other algorithms exhibited less stable outcomes, especially in high dimensions, some runs for GA/HS may get stuck in higher regions of the valley, causing the median to remain high. Thus, for Rosenbrock, GWO demonstrated both the fastest and most dependable convergence, whereas GA and HS frequently struggled to make progress, and DE/PSO offered intermediate performance in both speed and accuracy.

Rastrigin Function Optimization Performance

The Rastrigin function posed a significant challenge for most algorithms, highlighting differences in their exploratory abilities. GWO dramatically outperformed the others on this function, achieving by far the lowest errors. At $D=10$, GWO was the only algorithm that reliably found a near-optimal solution, its median best fitness essentially reached 0. In stark contrast, all other methods stagnated at much higher error levels in 10 dimensions. By 200 iterations, PSO, HS, GA, and DE had median fitness values around 0.3, 0.5, 0.8, and 1.0 respectively, indicating that these algorithms frequently became trapped in Rastrigin's local minima and could not fully escape to the global basin within the run time. GWO's convergence curve, however, shows a sharp drop around iteration 40–60 leading to a near-zero error, implying a successful navigation through the rugged landscape to the true optimum. The presence of oscillations in GWO's error curve during convergence suggests that GWO explored multiple regions but ultimately stabilized to the best value, underscoring its balance of exploration and exploitation on this multimodal terrain. At higher dimensions, the performance disparities on Rastrigin remained pronounced. GWO continued to find much better solutions than the others: for example, at $D=30$ its median final fitness was around 5–10, and even at $D=50$ GWO's median error stayed near 10. In contrast, the competing methods all yielded relatively large errors at termination, showing little evidence of approaching the true optimum in these runs. At $D=30$, HS and GA achieved median finals of roughly 20–30, DE about 30, and PSO was highest around 40. By $D=50$, these medians degraded further: PSO and GA often remained around 50–60, and even the best of the rest (HS) was near 25–30. The consistently high error plateaus for DE, GA, HS, and PSO indicate that at least half of their runs were stuck in suboptimal minima even after extensive iterations. Moreover, PSO's particularly poor results in higher dimensions suggest a tendency to prematurely converge to suboptimal regions in the Rastrigin landscape, a known vulnerability of PSO without diversification mechanisms. Convergence speed mirrored these outcomes: GWO not only reached far lower errors but did so faster whereas the other algorithms showed slow, incremental improvements that flattened out early into a stagnation plateau. Regarding stability, GWO was clearly the most reliable on Rastrigin: the fact that its median is so low implies a high success rate across runs in finding very good solutions. The other algorithms displayed much less stable performance, in the sense that run outcomes were consistently mediocre or in some cases highly variable with no run reaching the true optimum. For instance, one might infer that none of GA's runs found the global minimum at 30 or 50 dimensions, given its consistently high median, GA's search process was not robust against Rastrigin's plethora of local minima. In summary, on the Rastrigin benchmark GWO demonstrated a markedly superior convergence ability and stability, whereas DE, PSO, HS, and GA all struggled, with PSO and GA performing the worst in high dimensions.

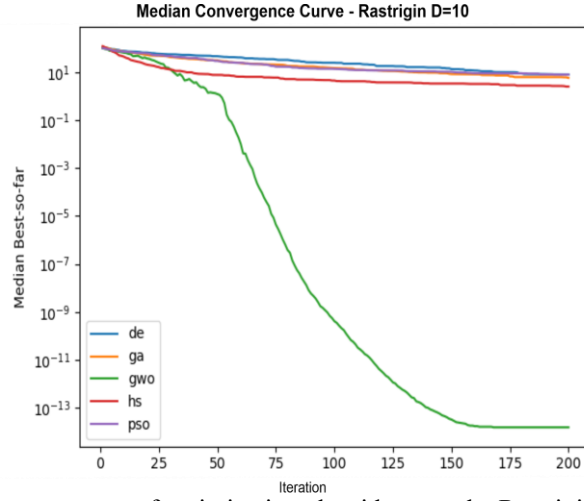


Figure 7. Median convergence curves of optimization algorithms on the Rastrigin benchmark function in 10 dimensions.

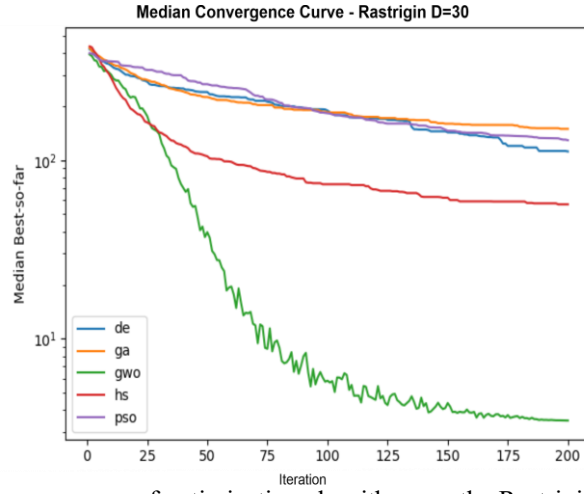


Figure 8. Median convergence curves of optimization algorithms on the Rastrigin benchmark function in 30 dimensions.

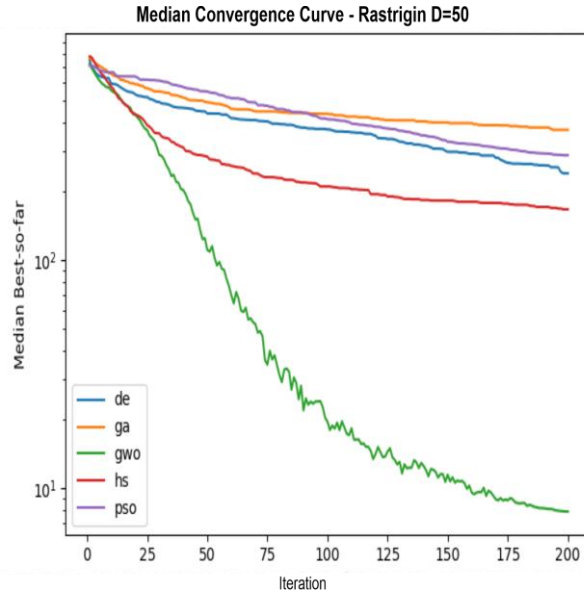


Figure 9. Median convergence curves of optimization algorithms on the Rastrigin benchmark function in 50 dimensions.

Ackley Function Optimization Performance

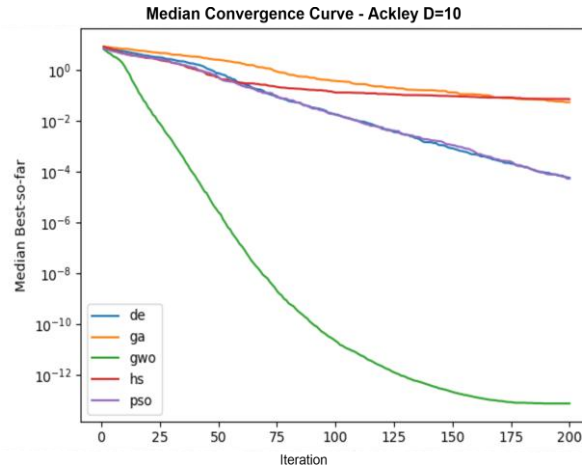


Figure 10. Median convergence curves of optimization algorithms on the Ackley benchmark function in 10 dimensions.

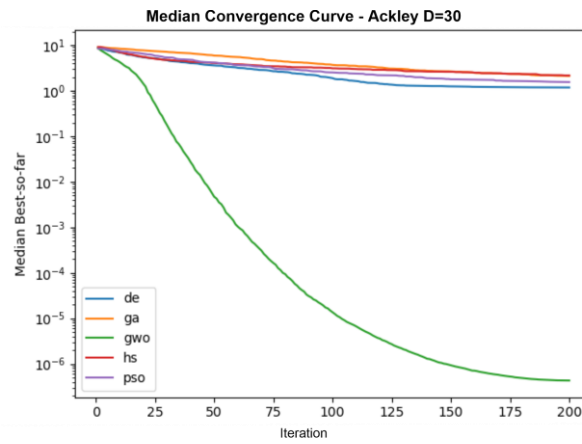


Figure 11. Median convergence curves of optimization algorithms on the Ackley benchmark function in 30 dimensions.

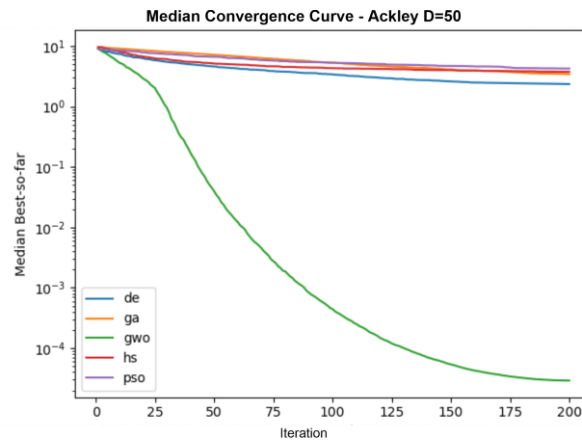


Figure 12. Median convergence curves of optimization algorithms on the Ackley benchmark function in 50 dimensions.

The Ackley function also differentiates the algorithms' performance, though its landscape features a broad basin which can facilitate convergence once an algorithm escapes the peripheral local optima. The results show a similar ranking to Rastrigin: GWO achieved the best performance by a wide margin, while GA consistently performed the worst, with DE, PSO, and HS in between. At $D=10$, GWO nearly reached the global optimum, effectively solving the function in most runs. DE and PSO also managed to reduce the error substantially for 10 dimensions though these were still several orders of magnitude higher than GWO's result. HS showed a slower

convergence, ending around 10^{-3} . GA, in contrast, barely improved after an initial drop: its median stagnated around 10^{-1} , indicating that GA struggled significantly with Ackley's multimodal landscape even in a low-dimensional case. This poor performance of GA suggests difficulty in maintaining diverse solutions, leading to premature convergence on one of the many local optima. As dimensionality increased, the gap between GWO and the other algorithms remained large. In 30 dimensions, GWO's median final fitness was on the order of 10^{-6} , whereas the next best algorithm (DE) stopped around 10^{-2} . PSO and HS finished with medians in the 10^{-2} range, and GA remained an outlier with an order-of magnitude higher error. By D=50, GWO still obtained a remarkably low median error, showing its scalability and effective exploration of Ackley's search space. All other methods, however, stagnated at much higher error levels by iteration 200: DE, PSO, HS were all clustered with final medians roughly (30–50% of the initial range). GA again performed worst, with a similar 10^{-1} plateau as in lower dimensions, suggesting it failed to make meaningful progress in most runs. The convergence trajectories underscore these differences: GWO's error curve drops rapidly and continuously, whereas GA's curve flattens very early, and DE/PSO/HS show moderate declines that level off well above zero. In terms of run-to-run consistency, GWO provided not only the lowest errors but also reliably so – most GWO runs found near-optimal regions (reflected in the very low median). The other algorithms had more consistent failure to fully converge (especially GA, which consistently got stuck at a relatively high error, yielding a narrow but high-error distribution of final results). One might say GA was “consistently bad” on Ackley, whereas PSO and DE were somewhat inconsistent, occasionally finding better minima but often not, leading to higher median error and presumably larger variance. HS was moderately reliable but its best efforts still fell short of the optima. Overall, Ackley results reinforce the earlier observations: GWO's balance of exploration and exploitation enabled superior and stable convergence even in complex landscapes, while GA's lack of diversity maintenance led to premature convergence and poor outcomes. DE, PSO, and HS achieved intermediate performance, with DE generally a bit better on Ackley (owing to its inherent mutation-based search diversity), and PSO/HS struggling when confronted with many local optima.

Computational Cost and Efficiency Analysis

From a CPU usage perspective, GA was the lightest algorithm with a stable consumption of around 100 percent, meaning it used only a single processor core. In contrast, PSO and GWO were the most CPU intensive algorithms. PSO showed an increase in CPU demand over iterations, rising from 100 percent at the start to a peak of 142 percent by iteration 200. GWO also recorded a peak of 138 percent at iteration 135, while DE and HS ranged between 108 percent and 115 percent. In terms of memory usage, all five algorithms demonstrated good efficiency with average consumption around 37.3 MB. GWO recorded the highest usage at 37.5 MB, followed by HS and PSO at approximately 37.4 MB, while GA and DE remained around 37.3 MB. These differences of a few hundred kilobytes are not practically significant and remain well within the memory capacity of the Raspberry Pi. Therefore, memory was not a limiting factor in these tests and the differences in computational cost were primarily driven by CPU usage. These findings highlight a trade-off between convergence performance and computational efficiency on a resource limited device. GWO, which was the most consistently high performing algorithm across all benchmark functions, also incurred some of the highest CPU utilization.

It leveraged the Pi 5's multicore capabilities to achieve its rapid convergence, essentially trading higher energy and CPU time for better solutions in fewer iterations. PSO and DE, which also performed well (especially on easier functions), similarly used more CPU on average. In contrast, GA's very low CPU usage came at the cost of much slower and poorer convergence; it conserved processor time but often failed to reach the best solutions within the iteration budget. HS occupied a middle ground, both in solution quality and resource use. From a practical standpoint, if a practitioner's priority is to obtain the best possible solution quickly (and the hardware can tolerate heavy CPU loads), algorithms like GWO or DE/PSO are advisable. They will find optima faster but will draw more power and CPU cycles in the process. On the other hand, if minimal CPU usage or thermal output is critical (for example, in battery-powered or thermally constrained scenarios), one might lean toward GA or HS, with the understanding that the solution quality may be suboptimal or require many more iterations to improve. Ultimately, the Raspberry Pi 5 experiments demonstrate that GWO offers an excellent balance of solution quality and reasonable resource use for these benchmark problems, whereas GA is computationally frugal but converges unreliably, and the other methods (DE, PSO, HS) fall on a spectrum between these extremes. This combined evaluation of convergence behavior and computational cost provides a nuanced basis for selecting a metaheuristic algorithm that best meets the specific performance and resource constraints of a given application.

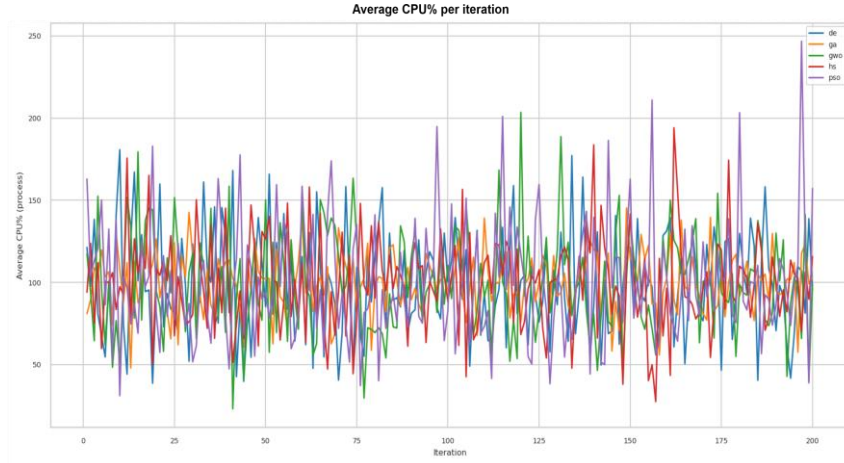


Figure 13. Average CPU% usage per iteration for each algorithm.

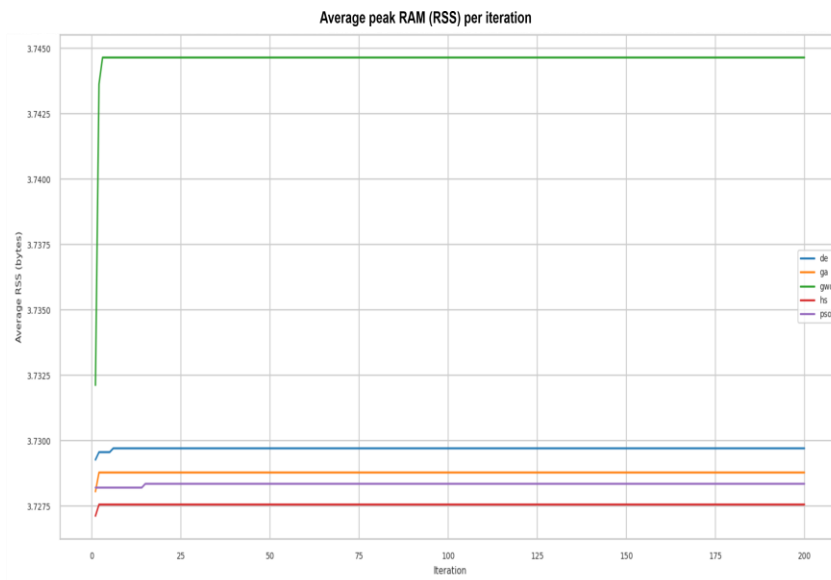


Figure 14. Average RAM (RSS) usage per iteration for each algorithm.

Table 1. Comparative summary

Algorithm	Convergence Quality	CPU Cost	Memory Usage	Recommended Scenario
GWO	Excellent	High	Low	Real-time optimization, high-accuracy requirements, when CPU load is acceptable
PSO	Good	High	Low	Applications needing good convergence with moderate CPU tolerance
DE	Good	Moderate	Low	Rugged or complex landscapes; balanced resource constraints
HS	Fair	Moderate	Low	Moderate resource limits; tasks where slower convergence is acceptable
GA	Poor	Low	Low	Extremely CPU-constrained environments; background or non-critical optimization

From an edge-software perspective, these results support selection rules based on the required convergence reliability and the acceptable CPU budget. GWO is the best fit when solution quality and fast convergence are primary and higher CPU activity is tolerable (e.g., time-sensitive edge optimization or control). PSO and DE provide strong alternatives when a balanced compromise is needed. GA and HS are more appropriate for low-priority or background optimization where CPU load must be minimized, and slower or less reliable convergence is acceptable. As an engineering refinement, adaptive mechanisms such as early stopping or resource-aware tuning can further reduce overhead when deploying these methods on constrained devices.

Conclusion

In summary, this work offers a controlled, device-level benchmark of five metaheuristics (DE, GA, GWO, HS, PSO) on a Raspberry Pi 5 across four canonical functions (Sphere, Rosenbrock, Rastrigin, Ackley) and three dimensions, jointly evaluating convergence behavior and computational cost (CPU/RAM). The results show that GWO is the most effective overall, consistently achieving the fastest and most stable convergence and the best final solution quality, while GA is the most lightweight in terms of CPU and memory but yields the weakest optimization outcomes within the fixed budget. DE and PSO provide solid middle-ground performance, typically converging substantially better than GA and sometimes approaching GWO on easier landscapes, whereas HS is competitive in select cases but generally trails GWO. These findings underscore a clear trade-off on edge devices: GWO is preferred when rapid, reliable convergence is paramount and higher CPU use is acceptable; GA suits ultra-constrained deployments; DE/PSO/HS balance effectiveness and efficiency. Future work should validate these insights on real-world edge tasks, broaden the benchmark suite (e.g., constrained/dynamic functions and higher dimensions), explore adaptive or self-tuning variants that respond to resource/progress signals, and incorporate energy/thermal profiling to identify truly sustainable, edge-ready optimizers.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author(s) Information

Ziadan Qowi

Bandung Institute of Technology
Bandung, West Java, Indonesia
ORCID iD: <https://orcid.org/0009-0004-0423-4354/>
*Contact e-mail: Ziadan.qowi97@gmail.com

Akhdan Musyaffa Firdaus

Bandung Institute of Technology
Bandung, West Java, Indonesia
ORCID iD: <https://orcid.org/0009-0000-1030-9077>

Hari Purnama

Bandung Institute of Technology
Bandung, West Java, Indonesia
ORCID iD: <https://orcid.org/0009-0005-6474-9840>

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Reasserting the Epistemic Role of Non-Parallel Line Contexts in Introducing Angle Relationships

Herizal Herizal

Indonesia University of Education

Nanang Priatna

Indonesia University of Education

Sufyani Prabawanto

Indonesia University of Education

Al Jupri

Indonesia University of Education

Abstract: Angle relationships are an important topic in Euclidean plane geometry and form a conceptual basis for understanding line parallelism. In scholarly geometry, these relationships were introduced through configurations of two non-parallel lines intersected by a transversal. However, in several instructional contexts, angle relationships were presented first through the context of parallel lines. This practice risked obscuring the epistemic status of angle relationships within the structure of Euclidean geometry. This study aimed to reaffirm the epistemic role of non-parallel line contexts as the conceptual foundation for introducing angle relationships. A qualitative study was adopted. Data were collected through both of the analysis of mathematical documents such as geometry textbooks and Focus Group Discussion (FGD) involving scholars in geometry, pure mathematics, and advanced mathematics education. The analysis focused on logical coherence and structural relationships among concepts. The results showed that the configuration of non-parallel lines provided the most conceptually neutral framework for introducing angular relationships. This can be seen, among other things, from the use of the term special pair of angles (in this case same-side interior angles) in Euclid's parallel postulate. Consequently, angle congruences or supplementary were interpreted as consequences of Euclid's fifth postulate rather than as their conceptual origin. These findings highlight the epistemic necessity of introducing angle relationships through non-parallel contexts to preserve coherence and conceptual hierarchy in Euclidean geometry.

Keywords: Angle relationships, Euclidean plane geometry, Non-parallel line, Parallelism

Introduction

The angle relationships formed when two lines are intersected by another line, referred to as a transversal, constitute a fundamental structure in plane geometry, particularly within the framework of Euclidean Geometry. The relationships between specific pairs of angles that arise serve as the foundation for understanding the concept of parallelism as well as theorems related to Euclid's fifth postulate, such as the criteria for parallel lines and the properties of parallel lines (Lewis, 1968; Prenowitz & Jordan, 1965). Various geometry literatures note that these angle relationships do not emerge as a consequence of line parallelism; rather, they originate from the intersection of any two lines with a transversal in a plane (Leonard et al., 2014; Lewis, 1968).

In the study of scholarly knowledge in geometry, the introduction of angle relationships begins with the configuration of two non-parallel lines intersected by a transversal (Lewis, 1968; Moise, 1990). This context represents the general setting in plane geometry, where angle relationships can be analyzed without additional assumptions. Parallelism is then introduced as a special condition that constrains the line configuration so that certain angle relationships become invariant and can serve as criteria for parallelism (Lewis, 1968). Thus, from a geometrical hierarchy perspective, angle relationships precede the concept of parallelism.

In the practice of presenting geometry content, however, angle relationships are often introduced directly through the context of parallel lines. This approach has the potential to obscure the conceptual structure of geometry, as angle relationships may appear to depend on parallelism. Consequently, it can lead to implicit assumptions regarding the congruence of certain angle pairs, such as alternate interior angles, or the supplementary nature of other pairs, for instance, same-side interior angles (Herizal et al., 2025). This situation risks inverting the conceptual hierarchy in Euclidean geometry, where special conditions are treated as foundational. Moreover, it may foster misconceptions regarding the measures of certain angle pairs, for example, the assumption that corresponding angles are necessarily congruent (Herizal & Priatna, 2024).

From a mathematical epistemology perspective, the introduction of concepts should follow a general-to-special principle, moving from the most general structures to specific cases through the addition of assumptions or postulates (Carter, 2024; Morales-Carballo et al., 2024). From a philosophical perspective, this reflects Hilbert's axiomatic method, which organizes mathematical theories from basic propositions and examines how different parts, such as geometry, are interrelated (Hilbert, 1918). The configuration of two non-parallel lines intersected by a transversal provides the fundamental framework for understanding angle relationships as intrinsic properties of line intersections. Conversely, introducing them in the context of parallel lines makes it impossible to distinguish whether certain angle relationships arise from the intersection itself or are merely consequences of parallelism.

Although this distinction is conceptually crucial, the mathematical justification for introducing angle relationships through non-parallel line contexts is rarely discussed explicitly. Considering the potential disruption of the epistemological structure of angle concepts when using parallel line contexts, this study aimed to reaffirm the epistemic role of non-parallel line contexts as a conceptual foundation for introducing angular relationships in Euclidean geometry, ensuring that such relationships were understood as a geometric structure that preceded and was independent of the concept of parallelism. In line with this objective, the study was designed to address the research question: What is the epistemic role of non-parallel line contexts in introducing angle relationships in Euclidean geometry?

Method

This study employed a qualitative approach. The investigation was directed toward examining the role of two non-parallel lines in establishing specific angle relationships within the structure of Euclidean geometry, prior to the introduction of the concept of parallelism. The qualitative approach enabled an in-depth exploration (Creswell, 2014). In this study was the exploration of the mathematical justifications and conceptual considerations regarding the object of study, non-parallel lines and their angle relationships, through various documents and expert perspectives.

Data were obtained from two primary sources. First, a documentary analysis of mathematical texts, including geometry textbooks representing scholarly knowledge in geometry. This analysis aimed to identify the conceptual sequence and structural relationships between angle relationships and parallelism in plane geometry. Second, a Focus Group Discussion (FGD) involving academics with expertise in geometry, pure mathematics, and advanced mathematics education. The FGD focused on epistemic discussions, particularly regarding the status of angle relationships, the generality of non-parallel line contexts, and the conceptual implications of introducing angular relationships directly through parallel line configurations. The FGD was employed to explore and test arguments concerning the necessity of introducing angular relationships using non-parallel line contexts.

Data from the documentary analysis and FGD transcripts were analyzed with an emphasis on the coherence of the material's structure and its mathematical justification. Emergent themes were synthesized to address the research question concerning the epistemic necessity of introducing angular relationships through non-parallel line contexts. Analytical validity was ensured through source triangulation and internal consistency between the study's objectives, the research question, and the resulting conceptual conclusions. Figure 1 showed the process.

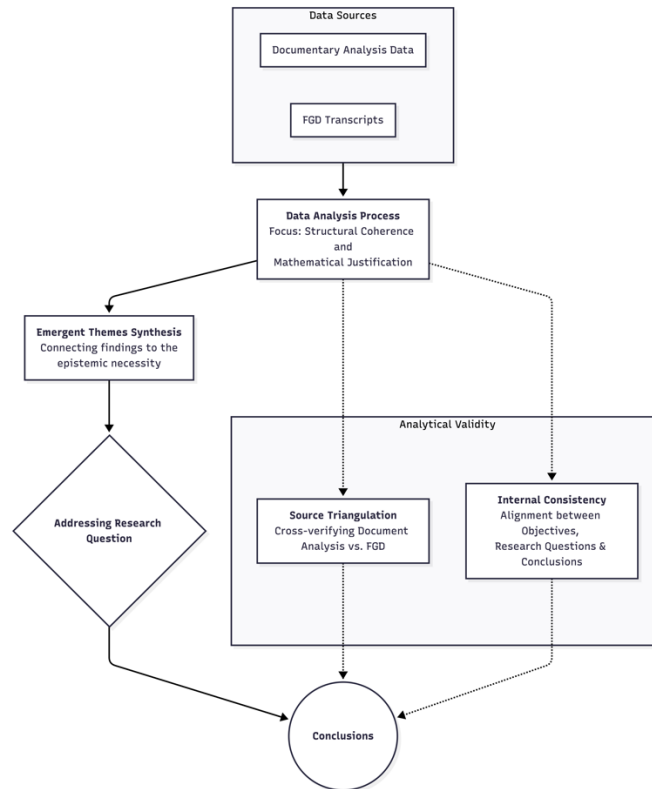


Figure 1. Data analysis process

Results and Discussion

This section presents the findings, accompanied by a discussion based on the analysis of mathematical documents and the arguments of participants during the Focus Group Discussion (FGD), with a focus on the epistemic role of the two non-parallel line context in the introduction of angle relationships.

Scholarly Knowledge of Angle Relationships

All mathematical concepts originally stem from knowledge developed by mathematicians. In the framework of didactic transposition, such knowledge is referred to as scholarly knowledge (Bosch & Gascón, 2006; Chevallard & Bosch, 2020b) and is considered a priori. The concept of forming angle pairs when two lines are intersected by a transversal represents an initial study prior to discussing parallelism. To arrive at the concept of angle relationships, two fundamental topics must first be discussed, as they serve as prerequisites for defining each specific type of angle pair formed. These two topics are transversal, and interior and exterior angles.

Transversal

A transversal is defined as a line that intersects two (or more) other lines at two distinct points, with all lines lying in the same plane (coplanar) (Alexander & Koeberlein, 2020; Clemens et al., 1990). Meanwhile, Lewis (1968) defined a transversal as a line that intersects two other lines at two different points. From these definitions, the characteristics of a transversal can be summarized as follows: (1) it intersects at least two lines, (2) the lines being intersected are arbitrary (not necessarily parallel), (3) it intersects the lines at distinct points (if three lines are involved, there are three distinct points of intersection), and (4) it lies in the same plane. Examples of a transversal and a non-transversal are shown in Figure 2, where in (i), line n is a transversal of lines m and l . In contrast, in (ii), line n is not a transversal of lines l and m because it does not intersect both lines at two distinct points.

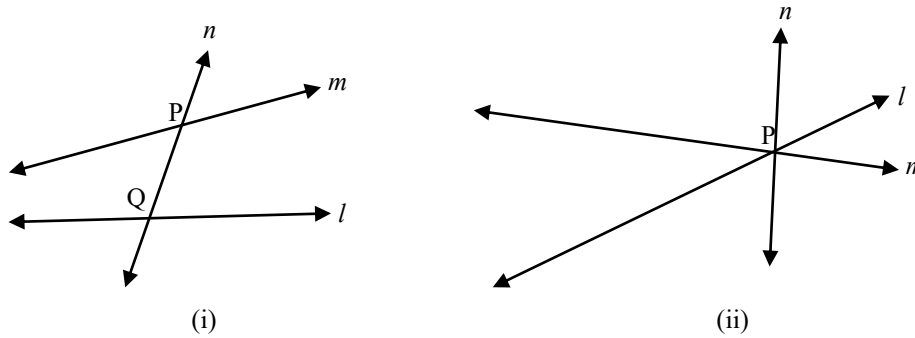


Figure 2. Illustration of transversal and non-transversal examples

Interior and Exterior Angles

When two lines are intersected by a transversal, four angles are formed at each point of intersection. Considering their positions relative to the two lines, some angles lie outside the lines while others lie between them. This distinction gives rise to the terms interior angles and exterior angles. Formally, if two lines r and s are intersected by a transversal t , the angles located between lines r and s are referred to as interior angles, whereas the angles outside lines r and s are called exterior angles (Alexander & Koeberlein, 2020; Lewis, 1968).

When any two lines are intersected by a transversal, eight angles are formed in total: four interior angles and four exterior angles. As illustrated in Figure 3, the exterior angles are $\angle 1$, $\angle 2$, $\angle 7$, and $\angle 8$, while the interior angles are $\angle 3$, $\angle 4$, $\angle 5$, and $\angle 6$. Identifying interior and exterior angles is crucial, as this concept forms the foundation for defining various specific angle pairs that arise when two lines are intersected by a transversal. From this explanation, it is clear that interior and exterior angles are formed whenever any two lines (not necessarily parallel) are intersected by a transversal.

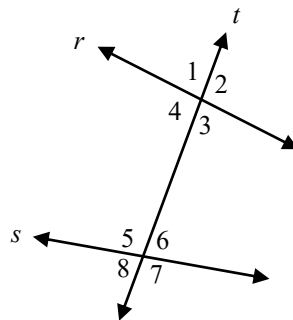


Figure 3. Illustration of two lines intersected by a transversal

Angle Relationships

The angle pairs formed, as shown in Figure 3, have specific names as follows:

1. Alternate interior angles: Two non-adjacent interior angles located on opposite sides of the transversal. There are two pairs of alternate interior angles: $\angle 3$ and $\angle 5$, $\angle 4$ and $\angle 6$.
2. Alternate exterior angles: Two non-adjacent exterior angles located on opposite sides of the transversal. There are two pairs of alternate exterior angles: $\angle 1$ and $\angle 7$, $\angle 2$ and $\angle 8$.
3. Same-side interior angles: Two interior angles located on the same side of the transversal. There are two pairs of same-side interior angles: $\angle 3$ and $\angle 6$, $\angle 4$ and $\angle 5$.
4. Same-side exterior angles: Two exterior angles located on the same side of the transversal. There are two pairs of same-side exterior angles: $\angle 1$ and $\angle 8$, $\angle 2$ and $\angle 7$.
5. Corresponding angles: Two non-adjacent angles located on the same side of the transversal such that one is an interior angle and the other is an exterior angle. There are four pairs of corresponding angles: $\angle 1$ and $\angle 5$, $\angle 3$ and $\angle 7$, $\angle 2$ and $\angle 6$, $\angle 4$ and $\angle 8$ (Alexander & Koeberlein, 2020; Clemens et al., 1990; Leonard et al., 2014; Moise, 1990).

Based on praxeology within the framework of the Anthropological Theory of Didactic (ATD) (Chevallard & Bosch, 2020a), the sequence of material described above can be organized into praxis and logos blocks. The praxis block includes tasks (T) and techniques (τ), while the logos block consists of technology (θ) and theory (Θ). Tasks (T) refer to the problems or situations presented, whereas techniques (τ) describe the methods or steps used to accomplish these tasks. Technology (θ) provides the rationale behind the choice of techniques employed, and theory (Θ) serves to justify or explain the technology, that is, the reasoning underlying the techniques used (Chevallard, 2019). Table 1 presents the arrangement of the aforementioned material organized within a mathematical praxeology framework.

Table 1. The mathematical praxeological organization of angle relationships

Task (T)	Techniques (τ)	Technology (θ)	Theory (Θ)
T ₁ : Explaining the Concept of a Transversal	τ_1 : Identifying lines that intersect two or more other lines at two or more distinct points	θ_1 : The conditions for a line to be a transversal are that it: (i) intersects two (or more) other lines, (ii) intersects them at two (or more) distinct points, and (iii) lies in the same plane	Θ_1 : Formal definition of transversal
T ₂ : Explaining the Concept of Interior and Exterior Angles	τ_2 : Identifying angles located between two lines intersected by a transversal and angles located outside the two lines intersected by a transversal	θ_2 : The condition for an interior angle is that it lies between two lines intersected by a transversal, and the condition for an exterior angle is that it lies outside the two lines intersected by a transversal	Θ_2 : Formal definition of interior and exterior angles when two lines intersected by a transversal
T ₃ : Identifying Specific Angle Pairs Formed When Any Two Lines Are Intersected by a Transversal	τ_3 : Identifying: (i) non-adjacent angles on the same side of a transversal, where one is an interior angle and the other is an exterior angle; (ii) two non-adjacent interior angles on opposite sides of the transversal; (iii) two non-adjacent exterior angles on opposite sides of the transversal; (iv) interior angles on the same side of the transversal; (v) two exterior angles on the same side of the transversal	θ_3 : The conditions for corresponding angles, alternate interior angles, alternate exterior angles, same-side interior angles, and same-side exterior angles	Θ_3 : Formal definition of corresponding angles, alternate interior angles, alternate exterior angles, same-side interior angles, and same-side exterior angles

The Context of Non-Parallel Lines as the Epistemic Foundation of Angle Relationships

Analysis of geometry textbooks indicated that the configuration of two non-parallel lines intersected by a transversal constituted the most fundamental conceptual context for understanding angle relationships in plane geometry. These angle pairs were formed whenever “any” two lines were intersected by a transversal, without the necessity of the lines being “parallel” (Leonard et al., 2014; Lewis, 1968; Moise, 1990). In this configuration, angle relationships did not arise as a consequence of any special condition but rather as a direct result of the intersection structure of two lines with a third line (the transversal) in the plane.

In other words, the configuration of two non-parallel lines intersected by a transversal provided the most natural framework for understanding angle relationships. In this context, the angles formed did not depend on additional assumptions such as parallelism but emerge directly from line intersections in the plane. This approach emphasizes that angle relationships precede and are independent of the concept of parallelism, allowing them to be understood as a universal geometric phenomenon. Furthermore, introducing angle relationships through non-parallel line contexts helps preserve logical clarity and the conceptual hierarchy in Euclidean geometry, where based on Lewis (1968), parallelism is understood as an additional condition that constrains line configurations and produces specific angle equalities, rather than serving as the primary source of angular relationships. In this way, the understanding of angle relationships becomes more conceptually and epistemically transparent, providing a solid foundation before studying the special case of parallel lines.

The Relationship Between Angle Relationships and Euclid's Parallel Postulate

Euclid, often referred to as the "Father of Geometry," was a Greek mathematician who lived around 325–265 BCE. He authored thirteen volumes, with Volume I, titled *Elements*, containing 23 definitions, five axioms, and five postulates (Boyer, 1968; Burton, 2011). One of Euclid's greatest contributions in *Elements* was the formulation of the five geometric postulates, which served as the foundation of the entire Euclidean geometry system. The parallel postulate originates from Euclid's fifth postulate, later known as Euclid's Parallel Postulate. Its statement is: "If a straight line intersects two other lines such that the sum of the interior angles on one side is less than two right angles (180°), then the two lines will eventually meet on that side if extended indefinitely" (Burton, 2011; Byrne, 1847).

The discussions from the FGD indicated that introducing the concept of angle pairs in the context of two non-parallel lines intersected by a transversal serves as a bridge to understanding Euclid's fifth postulate as shown in Figure 4. When Euclid's Fifth Postulate is linked to the angles formed by two non-parallel lines intersected by a transversal, the focus naturally falls on the same-side interior angles. The postulate states that if the sum of the interior angles on one side of the transversal is less than two right angles, then the lines will meet on that side if extended indefinitely. Within this framework, introducing angles through the context of two non-parallel lines is both appropriate and conceptual: the same-side interior angles central to the postulate emerge naturally from the line intersections without assuming parallelism. In other words, the non-parallel context provides a neutral foundation for understanding the parallel postulate, as the relevant angle relationships are already present and can be analyzed directly. This emphasizes that introducing angle relationships through non-parallel lines is not merely a visual representation but an epistemic necessity to maintain logical order and conceptual coherence in Euclidean geometry. Furthermore, it facilitates the comprehension of the parallel postulate.

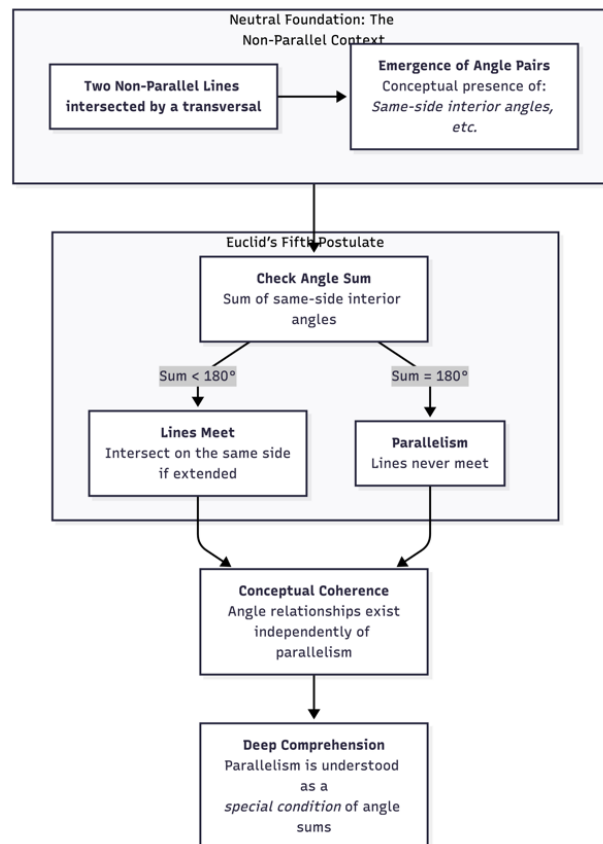


Figure 4. The epistemic foundation of non-parallel lines for Euclid's fifth postulate

When angle relationships are introduced first through non-parallel contexts, the application of the parallel postulate can be understood as a subsequent conceptual step that adds a structure to the pre-existing angle relationships. In this framework, parallelism does not serve as the source of angle relationships; rather, it acts as a condition that constrains the geometric configuration so that certain angle pairs become congruent or supplementary (Leonard et al., 2014; Lewis, 1968). This approach clarifies that angle equalities in parallel lines are an additional consequence, not the origin of the angle relationships themselves.

Non-Parallel Contexts to Avoid Potential Misconceptions

One important reason for introducing specific angle pairs through the context of non-parallel lines is to prevent misleading understandings. Figure 5 shows the logical reasoning behind this approach. If angle relationships are introduced directly in the context of parallel lines, learner or readers may mistakenly assume that angle congruences and certain relationships exist solely because the lines are parallel. In other words, parallelism might appear to be a necessary condition for the formation of specific angle pairs. This is not an exaggeration, as several studies have shown this (Herizal et al., 2025; Herizal & Priatna, 2024). In reality, angle relationships such as corresponding angles, alternate interior angles, or same-side interior angles are inherently established by the intersection of two lines by a transversal, without requiring the lines to be parallel.

Moreover, a parallel-line-based approach may lead to generalization errors, such as the belief that “corresponding angles are always congruent” or that other angle pairs, like alternate interior angles, must always be equal, without recognizing that such equalities are in fact specific consequences of the parallel postulate (Euclid’s Postulate V). A study by Herizal et al. (2025) showed these results. This phenomenon is related to learning obstacles, which Brousseau (1997) refers to as epistemological and didactical obstacles. By introducing angle relationships through a non-parallel context, it is emphasized that these relationships are universal and independent of parallelism. The non-parallel context separates general phenomena from special cases, resulting in a mathematical understanding that is logical, coherent, and hierarchical: angles emerge as local consequences of line intersections, while parallelism imposes additional constraints that produce specific congruences.

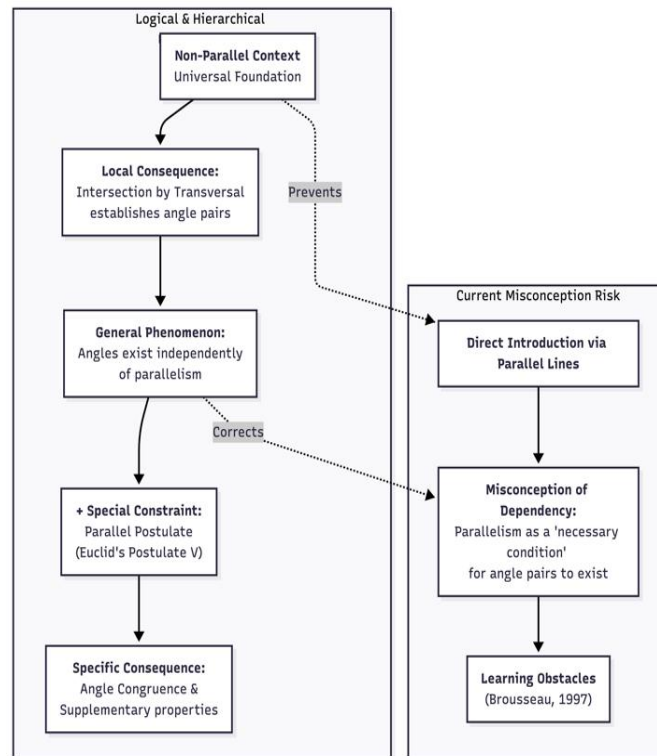


Figure 5. The role of non-parallel lines for supporting understanding and preventing misconception

Conclusion

This study reaffirms that the context of two non-parallel lines intersected by a transversal plays a fundamental epistemic role in the introduction of angle relationships in Euclidean geometry. Through the analysis of mathematical documents and expert discourse in Focus Group Discussions, it is shown that angle relationships constitute a geometric structure emerging directly from line intersections, independent of any assumption of parallelism. Thus, angle relationships conceptually precede and are independent of the concept of parallelism.

The findings indicate that the non-parallel line context provides the neutral conceptual framework for developing an understanding of angle relationships. In this context, angle relationships can be derived solely using basic geometric postulates, ensuring that their origin remains epistemically transparent. In contrast,

introducing angle relationships directly through parallel line contexts may obscure the dependence of certain angle relationships on line parallelism and, potentially, on Euclid's Fifth Postulate, while also reversing the internal hierarchy of concepts within the geometric structure. By establishing the non-parallel context as the starting point, parallelism can be properly understood as a subsequent axiomatic assumption that produces specific angle equalities, rather than serving as the primary source of angle relationships.

Recommendations

Based on these findings, it is recommended that the conceptual introduction of angle relationships in the study of geometry begin with the context of two non-parallel lines intersected by a transversal. This approach allows angle relationships to be understood as a general and independent geometric structure before the additional condition of parallelism is introduced.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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Author(s) Information

Herizal Herizal

Indonesia University of Education
Bandung, West Java, Indonesia
ORCID iD: <https://orcid.org/0000-0003-3360-0582>
*Contact e-mail: herizal_mathedu@upi.edu

Nanang Priatna

Indonesia University of Education
Bandung, West Java, Indonesia
ORCID iD: <https://orcid.org/0000-0003-2294-745X>

Sufyani Prabawanto

Indonesia University of Education
Bandung, West Java, Indonesia
ORCID iD: <https://orcid.org/0000-0003-2872-6535>

Al Jupri

Indonesia University of Education
Bandung, West Java, Indonesia
ORCID iD: <https://orcid.org/0000-0002-0485-4332>

*Corresponding author(s) contact email

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3D Accuracy Assessment of an Indoor UWB Positioning System for UAV Emergency Applications Using VICON Ground Truth

Ivanescu Georgiana-Florentina
Polytechnic University of Bucharest

Abstract: In recent years, amid the growing frequency of natural disasters and large-scale emergency scenarios, unmanned aerial vehicles (UAVs) have become essential tools for executing risky missions, without jeopardizing the lives of search and rescue personnel. While GNSS represents the most mature and robust positioning method, it becomes unreliable in indoor scenarios, as it is affected by multipath and non-line-of-sight (NLOS) conditions. This paper evaluates the 3D positioning accuracy of an ultra-wideband (UWB) indoor positioning system. The main purpose of this assessment is to decide whether the system can assure robust UAV positioning during emergency situations in GNSS-denied areas. The proposed system is rapid to deploy, cost-effective, and requires minimal hardware and software configuration, making it suitable for emergency response scenarios. The 3D trajectory estimated by the UWB positioning system is evaluated against ground truth positioning data provided by a VICON motion capture system. The system is tested in an uncontrolled indoor environment, with obstacles and NLOS conditions. In order to produce the best possible trajectory estimate, offline filtering techniques such as Kalman Filter, Savitzky-Golay filter and Rauch–Tung–Striebel smoothing are applied. The main purpose of these filters is to mitigate noise and the impact of outliers, and obtain a smoother and more reliable trajectory. A comparative analysis of Kalman Filter, Savitzky-Golay filter and Rauch–Tung–Striebel smoothing is presented by computing the Root Mean Square Error (RMSE) on each axis between the UWB measurements and the ground truth trajectory both before and after applying the offline filtering techniques.

Keywords: Indoor positioning, Unmanned aerial vehicles, Accuracy, Offline filtering

Introduction

These days, satellite navigation systems play a major role in the safe navigation and tracking of automobiles, ships and airplanes, as well as the positioning and monitoring of personal devices. Indoor localization has several uses in various domains, such as industry, mainly for asset tracking, emergency situations management and surveillance. Indoor positioning systems also represent critical infrastructure for some uprising concepts, such as internet of things (IoT) (Faheem Zahari, 2019). As people spend more time indoors, the main issues that occur concerning positioning services are related to their stability, accuracy and availability. In an urban setting, the GNSS receiver fitted on a modern mobile device can provide its location with an accuracy up to 7-13 meters (Krista Merry, 2019).

Additionally, tall buildings can block GPS signals, which leads to a multipath effect causing considerable positioning errors; thus, it often becomes difficult to determine whether the mobile terminal is located inside or outside the structure (Gyula Simon, 2021). Since the creation of contemporary smartphones, interest in developing more high-performance indoor positioning systems (IPS) has increased (Faheem Zahari, 2019), (Samama, 2019). Under high-stress, dynamic conditions, the rapid and precise positioning of people and certain goods can be critical. Previous research has investigated navigation solutions for GPS-denied environments, particularly through the integration of MEMS-based inertial navigation systems with GPS (Grigorie, 2017); however, such approaches typically provide only short-term positioning capability during signal outages, highlighting the continued need for reliable indoor positioning systems for sustained navigation in GNSS-denied scenarios. Thus,

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non-GNSS navigation systems must not only provide exact and continuous coordinates, but must also be resistant to certain error-inducing external factors. Based on signal type, IPS can be separated into two main categories: radio-based and non-radio based. Among the most widely-used radio-based technologies are Wi-Fi, BLE (Bluetooth low energy), and ultra-wideband (UWB), while non-radio technologies involve cameras, ultrasound, IMUs and other types of sensors (Tefay Gidey Hailu, 2024). Reference (Jiahao Huang, 2024) provides a comprehensive review of indoor localization technologies and positioning algorithms and summarizes positioning accuracy achieved by different technologies: UWB provides centimeter-level accuracy, magnetic plus inertial fusion yields an accuracy of 1-2.8m, while ultrasonic localization can offer a median error of 15 cm.

UWB systems are among the best alternatives to GNSS navigation in areas where the access to satellites is denied or difficult. The IEEE 802.15.4a standard was the earliest to incorporate UWB standards in 2007 (Eirini Karapistoli, 2010). Due to its very narrow time-domain pulses, UWB can achieve very high positioning accuracy. UWB systems use time of flight (ToF) or received signal strength (RSS) measurements for computing the distance between the fixed anchors and the mobile tag. The majority of papers report centimeter-level accuracy for UWB systems used in indoor scenarios (Paolo Dabove, 2018), (Janis Tiemann, 2015). Furthermore, reference (Cristian Vidan, 2023) analyzes the RSS through different thickness walls in order to determine whether an ad hoc and low cost UWB indoor positioning system can enable reliable indoor localization for drones, proving that the UAV can safely navigate in soft NLOS scenarios.

Unmanned aerial vehicles (UAVs) have gained increasing popularity over the last years, as they have started to execute more varied and ambitious assignments, both in military and civilian fields. For many of these tasks, UAVs need to navigate safely in GNSS-denied environments, such as industrial infrastructure, or residential buildings during emergency scenarios. This paper aims to determine whether a low-cost and quick-to-deploy UWB IPS can allow safe UAV indoor navigation by providing reliable and accurate positioning in line-of-sight and disrupted LOS conditions. This will allow the UAVs to provide information to the first responders about the number and health status of the wounded and other hazards inside different infrastructures following an earthquake, explosion or other. The UAV could be equipped with chemical or other detectors, so that it could detect a large spectrum of possible toxic substances released into the atmosphere. This could assure a rapid response time, without risking the lives of the first responders. Furthermore, UWB infrastructure could be preinstalled in airports, warehouses and other industrial buildings, allowing for immediate UAV navigation in case of emergency. By enabling reliable indoor localization, UWB systems can facilitate UAV navigation in GNSS-denied areas, increase operator situational awareness, and enhance the safety and effectiveness of emergency response operations.

In this paper, the emphasis will be put on surveying the accuracy and robustness of an UWB IPS under LOS and soft NLOS scenarios, in an uncontrolled environment. The accuracy of the 3D coordinates was demonstrated and evaluated in comparison to a MOCAP system; the results were quantified by computing the root mean square error (RMSE). By post-processing the collected data, respectively by applying offline filters, the overall performance of the UWB system was improved by ~8%. The novelty of this paper lies in the experimental evaluation of an indoor UWB positioning system for UAV applications employing the high-precision VICON motion capture data as ground truth, providing a realistic assessment of achievable 3D positioning accuracy in uncontrolled indoor environments. Furthermore, a comparative analysis of multiple offline filtering techniques, including Savitzky–Golay, Kalman, and Rauch–Tung–Striebel smoothing, is performed to quantify their influence on trajectory accuracy and to identify the most suitable method for improving UWB-based indoor localization performance.

System Description

UWB-based IPS

The UWB system consists of 4 anchors and one tag that was mounted on the UAV. One master tag will be connected to a laptop, in order to provide the coordinates, as well as other parameters of the slave tag installed on the UAV in real time, via the Arduino IDE. The anchors are powered by 4 external batteries and are arranged to make a rectangle, at different heights, in order to ease the process of establishing the coordinates of each anchor and minimize installation time. The distances between the anchors were accurately determined using a laser distance meter. The precision of the system greatly depends on the exactness of the anchor coordinates provided to the software.

The distance between the anchors and the tag at any given moment can be computed through multilateration; the

time-of-flight between the tag and the four beacons can be computed through two techniques: time difference of arrival (TDoA) and two-way ranging (TWR). This paper uses the TWR method for two main advantages: clock synchronization between anchors is not required, unlike TDoA, making the system simpler and faster to deploy; furthermore, TWR systems do not require wired synchronization or a master clock, making them easier to install and maintain. For the TWR method, the tag sends a data packet to each anchor to start the positioning process, then waits for an acknowledgment signal from the anchors. The time of flight of the signal, respectively the time in which the signal moves for the transmitter to the receiver, is calculated using the following formula (Rakshit Ramesh, 2020):

$$ToF = \frac{t_{total} - t_{reply}}{2} \quad (1)$$

where t_{total} is described as the interval of time between the tag's initial data packet transmission to when the tag receives the data packet from the beacon; t_{reply} is the time difference from the moment when the anchor receives a signal to when it sends one.

The distance between the tag and the anchors is calculated using the following equation:

$$d = c \times ToF \quad (2)$$

where $c = 3 \times 10^8$ m/s is the speed of light and ToF represents the time of flight of the signal. After having computed the distance between the tag and at least 3 anchors for 2D positioning and 4 anchors for 3D positioning, the (x,y,z) set of coordinates of the tag can be deduced from the following system:

$$\begin{cases} d_A = \sqrt{[(x_A - x)^2 + (y_A - y)^2]} \\ d_B = \sqrt{[(x_B - x)^2 + (y_B - y)^2]} \\ d_C = \sqrt{[(x_C - x)^2 + (y_C - y)^2]} \end{cases} \quad (3)$$

The four UWB anchors were installed at different heights to ensure adequate 3D positioning observability within the test area. Each beacon has a hexadecimal ID. The coordinates of the anchor with the smallest hexadecimal ID, were set to be (0,0,0), before overlaying it on the origin point of the Vicon system, as seen in (Figure 1). This alignment enabled direct comparison between the UWB and VICON position measurements.

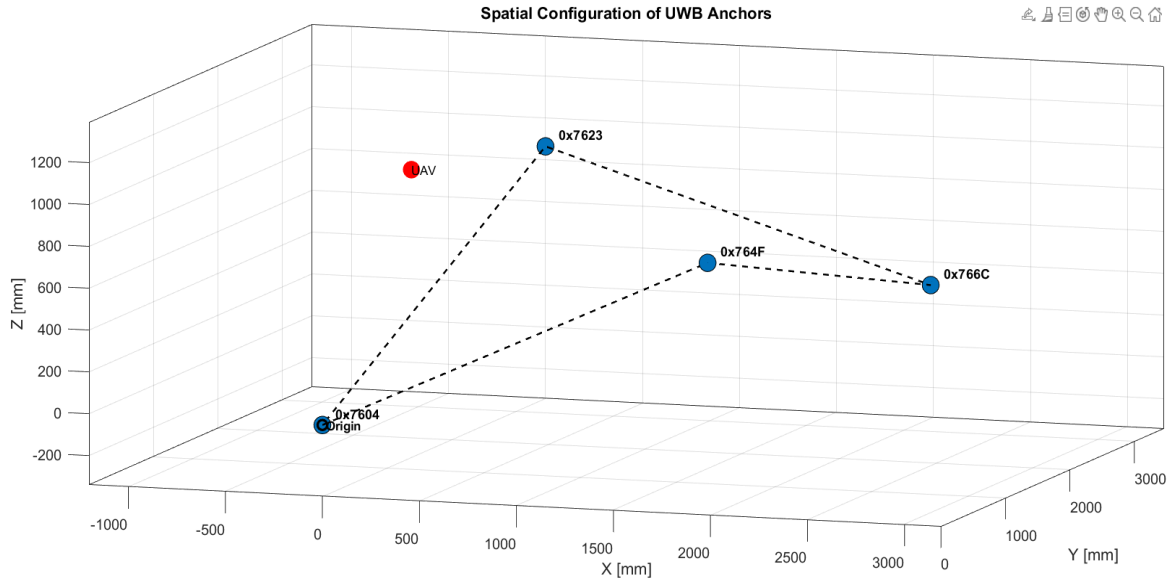


Figure 1. 3D layout of UWB anchors

VICON System

The ground truth position data used for accuracy evaluation was obtained using a VICON motion capture system. The Vicon MOCAP cameras emit infrared strobe lights once per frame. These lights are reflected by the

retroreflective markers attached to the object to be positioned. The 3D position of the tracked object is constructed by triangulating the marker positions observed by multiple cameras at the same moment. The cameras are equipped with optical filters that ensure that only light with the same wavelength as the emitted light reflects back into the camera. The 16 MOCAP cameras had been installed and calibrated in a 60 m² room prior to the testing of the UWB system. The cameras provide good coverage for the whole room. The motion capture system provides sub-millimeter accuracy under optimal conditions (Vicon, 2020), making it suitable as a reference system for evaluating positioning accuracy. The maximum error at a given point during the experiment was 9 mm, with the majority of the errors having values below 2 mm. The VICON motion capture system is considered a reliable ground truth reference due to its very high positioning accuracy and stability. Furthermore, it is not affected by drift, as position estimates are obtained directly from optical measurements and not through integration. This ensures consistent position measurements throughout the entire experiment.

During the calibration process, the VICON system defines its own global coordinate system, with a fixed origin and axis orientation. In order to allow direct comparison between the UWB and VICON position measurements, the coordinate systems of both systems were aligned by colocating one of the UWB anchors with the origin of the VICON coordinate system. The VICON system operates at a much higher sampling frequency compared to the UWB positioning system, providing continuous and accurate trajectory measurements. This highlights the portions of the trajectory where UWB measurements are interrupted due to poor LOS between the tag and the beacons.

The retroreflective markers are placed on the extremities of the UAV. The trajectory of each marker can be followed separately, as well as the trajectory of the center of mass of the volume delimited by the markers. The spatial configuration of the VICON motion capture system is illustrated in (Figure 2). 16 infrared cameras are positioned around the experimental area to ensure full coverage of the capture volume and enable accurate 3D position tracking.

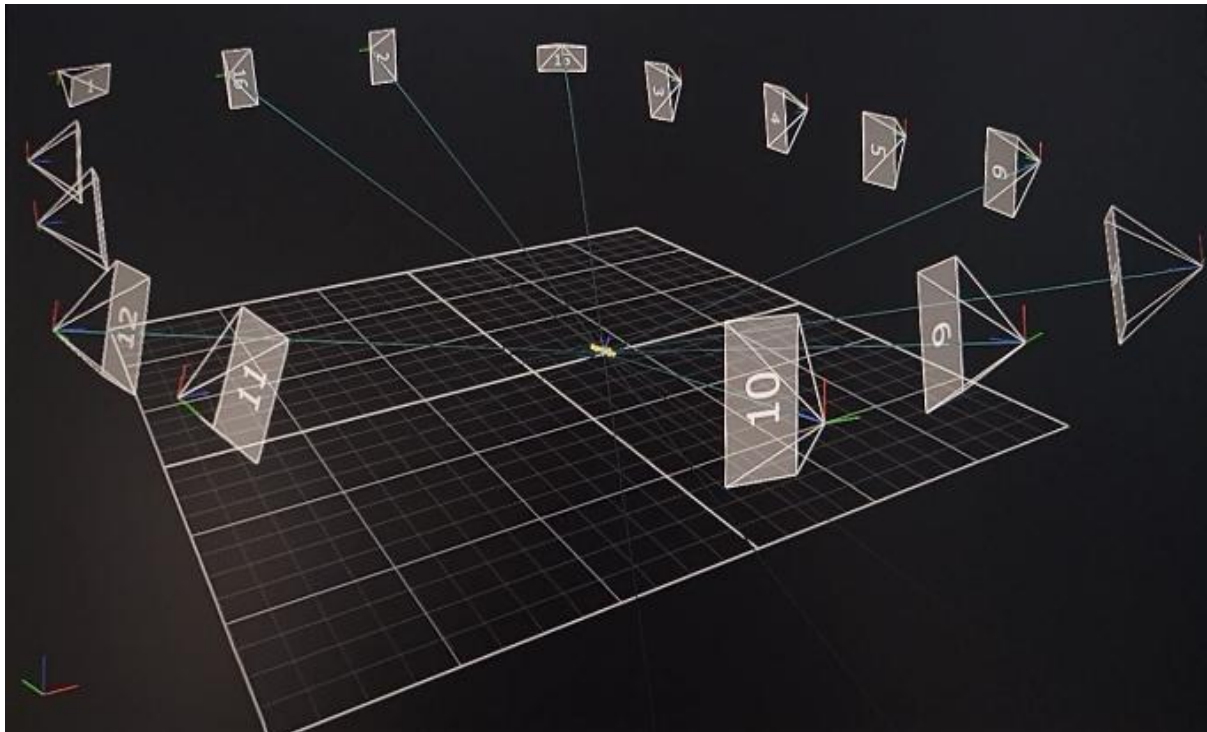


Figure 2. Spatial distribution of the VICON cameras

Experimental Setup

A UWB tag and reflective markers were attached to the UAV, allowing simultaneous tracking by both systems. The complete configuration of the UWB anchors and the VICON cameras is illustrated in (Figure 3). Position data from both systems were recorded simultaneously. Four UWB anchors were installed at fixed positions, within the capture volume defined by the VICON cameras. The UAV was moved along an arbitrary trajectory in order to evaluate positioning accuracy under dynamic conditions. The coordinate systems of the two IPS were aligned

by colocating one of the UWB anchors with the origin of the VICON coordinate system. The UWB data was collected through Arduino, while the VICON Tracker software provides an Excel file containing the 3D coordinates for each frame.

One important issue for the accuracy testing was raised by the different update rates of the two systems. The Vicon Tracker software enables the user to manually change the refresh rate of the positions, with the usual update rates being between 200-300Hz, while the UWB system only allows refresh rates between 10-15 Hz. In order to ensure temporal consistency and enable accurate comparison, the VICON trajectory was downsampled to match the update rate of the UWB system.

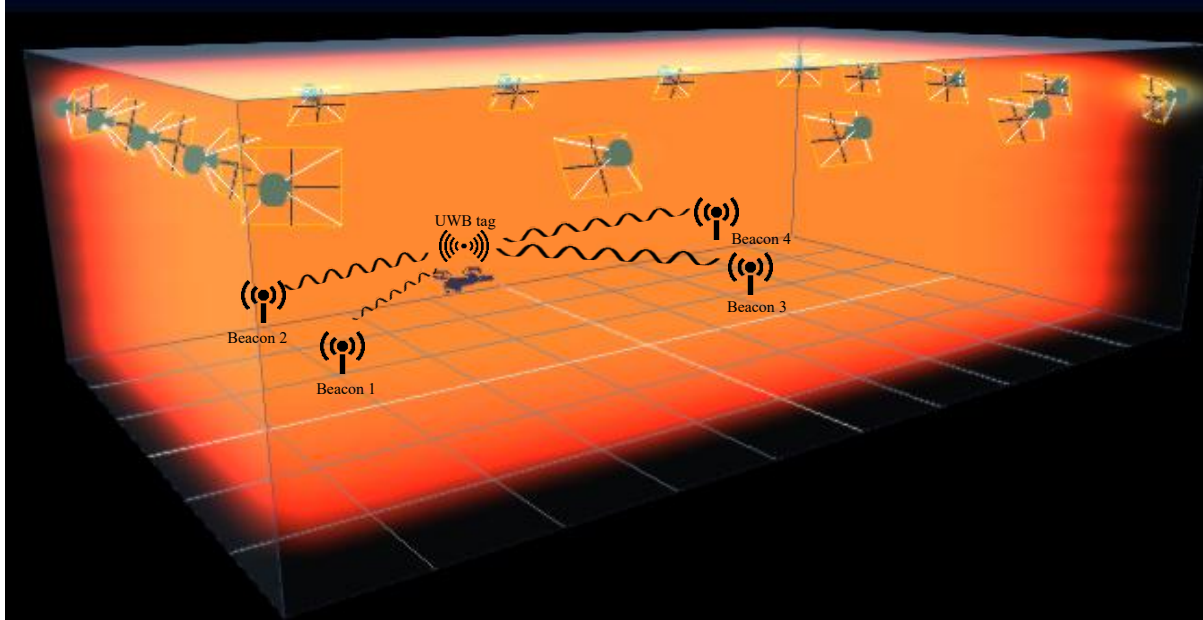


Figure 3. Experimental setup of the VICON and UWB systems

The coordinates were plotted against time, in order to obtain the trajectory of the UAV on all three axes. As the UWB generated coordinates were very affected by noise and other positioning errors, the main focus was to find a suitable filter, that would follow the trend of the trajectory while mitigating the problems generated by the noise and outliers.

Accuracy Testing

The positioning error was computed on each axis as the difference between the UWB position and the Vicon ground truth. To quantify the positioning accuracy, the RMSE was computed for each axis using the following formulas:

$$\begin{aligned} RMSE_x &= \sqrt{\frac{1}{N} \sum_{i=1}^N (x_{UWB}(i) - x_{VICON}(i))^2} \\ RMSE_y &= \sqrt{\frac{1}{N} \sum_{i=1}^N (y_{UWB}(i) - y_{VICON}(i))^2} \\ RMSE_z &= \sqrt{\frac{1}{N} \sum_{i=1}^N (z_{UWB}(i) - z_{VICON}(i))^2} \end{aligned} \quad (4)$$

where N represents the total number of samples.

The UWB trajectory was compared to the VICON ground truth trajectory in order to visualize the positioning performance.

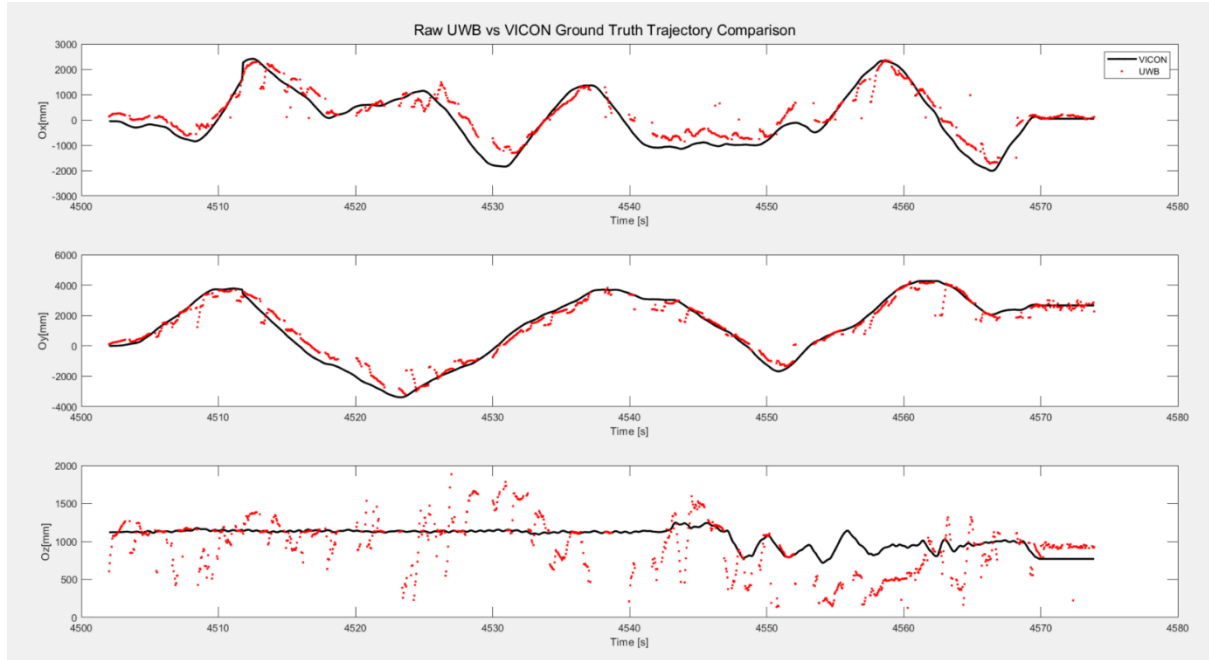


Figure 4. Shows the position of the UAV along the X, Y, and Z axes as a function of time, compared to the VICON ground truth trajectory. Figure 4. UWB and VICON trajectory comparison

The results show that the raw UWB coordinates generally follow the ground truth trajectory but exhibit noticeable fluctuations and outliers caused by measurement noise, propagation errors, and suboptimal system geometry. These effects cause positioning errors and reduce the accuracy of the estimated trajectory. However, the UWB system provides a centimeter-level accuracy. RMSE values for each axis are summarized in (Table 1).

Table 1. RMSE values for X, Y and Z axes

Axis	RMSE [mm]
X	625.8
Y	813.9
Z	322.0

The results show that the positioning error varies across the three axes, with the largest error being on the Y axis. This can be attributed to the geometric layout of the UWB anchors, which affects the positioning accuracy depending on the position of the UAV within the volume determined by the anchors. The spatial distribution of the anchors influences the geometric dilution of precision (GDOP), which leads to different accuracies on the axes. The geometric dilution of precision reaches a minimum value near the center of the measurement volume; as the UAV moves closer to the edges of the anchor distribution, the GDOP increases, resulting in larger positioning errors. Furthermore, part of the UAVs trajectory was beyond the anchor-delimited measurement volume, thus proving that the UWB system is reliable even under degraded communication conditions and difficult line-of-sight scenarios. The Z axis is the most affected by noise, especially in the more dynamic section of the trajectory. Both the static and dynamic portions of the trajectory contain noise and outliers, even though there are areas where the UWB coordinates match the ground truth.

These results are realistic for an emergency situation, where the rapid deployment of the system is critical. The suboptimal 3D layout of the anchors, as well as the obstacles in the room, which cause difficult propagation of the signals, are the main causes of the positioning errors. Despite these errors, the UWB system is able to provide continuous 3D position estimates and accurately track the overall motion of the UAV within the experimental area. These results demonstrate that the UWB positioning system provides reliable position information, even in uncontrolled environments, while also highlighting the presence of measurement noise and positioning errors that can be further reduced using filtering techniques.

Offline Filtering

Although the raw UWB coordinates follow the general shape of the ground truth trajectory, noticeable fluctuations and frequent outliers are observed due to measurement noise, multipath propagation, and inadequate geometry of

the anchor configuration. These effects cause positioning errors that reduce the overall accuracy of the system. To mitigate these effects and evaluate the maximum achievable positioning performance, several offline filtering techniques were applied to the raw UWB trajectory. As it allows processing of the complete dataset, offline filtering is useful tool in experimental evaluation. Unlike real-time filtering methods, offline approaches have access to the entire sequence of measurements, enabling more effective noise reduction and trajectory smoothing. As a result, the motion of the UAV can be reconstructed more precisely and compared to high-precision ground truth data. In this study, three filtering methods were applied to the raw UWB trajectory: the Savitzky–Golay filter, the Kalman filter, and the Rauch–Tung–Striebel (RTS) smoother.



Figure 5. Savitzky–Golay filtering performance

The Savitzky–Golay filter was used as a signal smoothing technique to mitigate high-frequency measurement noise while preserving the general shape of the trajectory. This filter produces a smoothed output signal by fitting a low-order polynomial to a sliding window of data samples. The Savitzky–Golay filter improves trajectory smoothness and successfully eliminates the majority of outliers, as shown in (Figure 5).

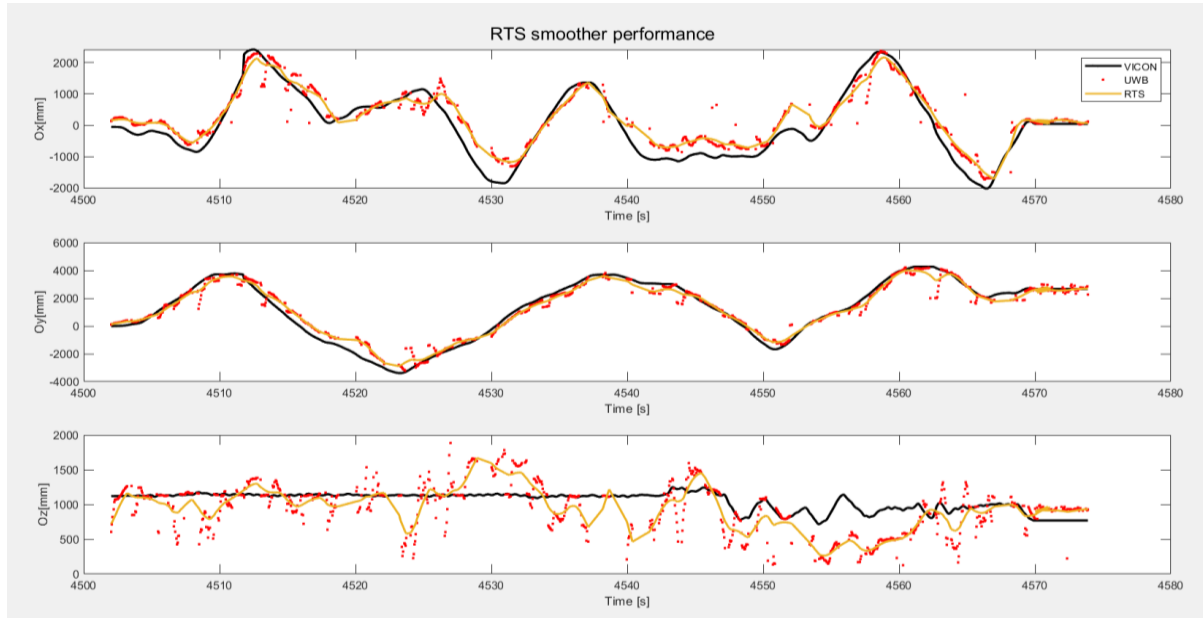


Figure 6. Kalman filter trajectory estimation performance

The Kalman filter was applied in order to improve position estimation by combining the UWB measurements with a dynamic motion model. The filter estimates both position and velocity and accounts for measurement uncertainty and the dynamics of the system. This approach improves trajectory stability and reduces the impact of measurement noise, resulting in more consistent and robust position estimates. However, the Kalman filter applied is a forward-only filter and cannot fully exploit the whole dataset, as it only uses current and past measurements to estimate the state of the system. (Figure 7) highlights the performance of the Kalman filter versus the ground truth trajectory.

While the Kalman filter offers good results, it is possible to further improve the trajectory estimation, by applying the Rauch–Tung–Striebel smoother as an offline extension of the Kalman filter. Unlike the standard Kalman filter applied, which operates in a forward direction, the Rauch–Tung–Striebel smoother performs an additional backward pass through the data, utilizing both past and future measurements. This allows more accurate estimation of the trajectory and provides improved noise reduction compared to forward-only filtering methods. Although this filtering method has no real-time applications, it is a useful tool in evaluating the maximum achievable positioning accuracy of the UWB system.



Figure 7. RTS smoother trajectory estimation performance

On the X and Y axes, the RTS smoother significantly reduces high-frequency noise and minimizes the oscillations more effectively than the Kalman filter. On the Z axis, although not all errors caused by geometric constraints could be corrected, the RTS smoother visibly reduces random fluctuations compared to the raw data, thus improving the accuracy.

The performance of the filtering methods was evaluated by comparing the filtered UWB trajectories with the VICON ground truth and computing the RMSE for each axis. The results show that offline filtering significantly increases the positioning accuracy by reducing measurement noise and producing a smoother and more accurate trajectory estimate. Among the evaluated methods, the RTS smoother provides the best overall performance, achieving the lowest positioning error. (Table 2) summarizes the RMSE values on all three axes for the studied offline filters.

Table 2. RMSE comparison of offline filtering methods

Filter	RMSE X [mm]	RMSE Y [mm]	RMSE Z [mm]
Savitzky–Golay	610.7	802.9	306.5
Kalman Filter	622.4	804.9	307.7
RTS Smoother	591.6	764.4	259.9

The results demonstrate that offline filtering improves the positioning accuracy of the UWB system compared to the raw measurements. The Savitzky–Golay filter provides moderate improvements, reducing the RMSE by 2.41% on the X axis, 1.35% on the Y axis, and 4.81% on the Z axis. The Kalman filter achieves a similar performance as the SG filter, with improvements of 0.54%, 1.11%, and 4.44% along the X, Y, and Z axes. The

most significant positioning improvement is obtained using the RTS smoother, which reduces the RMSE by 5.47% on the X axis, 5.71% on the Y axis, and 19.29% on the Z axis compared to the raw UWB measurements. The substantial improvement on the vertical axis highlights the advantage of smoothers that can exploit the whole dataset in mitigating noise and geometric limitations.

In terms of overall performance, the Savitzky-Golay filter achieves a 2.36% improvement compared to the raw UWB measurements on all the 3 axes, while the Kalman filter provides a 1.52% improvement. The RTS smoother provides the most significant enhancement, reducing the overall positioning error by 8.11%. The most important improvement is observed on the vertical axis, where the RTS smoother reduces the RMSE by 19.29%. Overall, the results confirm that offline smoothing techniques, particularly RTS, significantly increase trajectory accuracy and provide a more reliable representation of the UAV motion within the measurement volume.

Conclusions

The experimental evaluation confirms that the raw UWB positioning system is capable of tracking the overall UAV dynamics within the indoor environment with centimeter-level accuracy; however, the measurements are affected by noise, outliers, and geometric limitations due to the anchor configuration. These factors introduce deviations from the ground truth trajectory, most prominently along the vertical axis, where the GDOP has a stronger influence.

The Savitzky-Golay filter successfully removes high-frequency oscillations and attenuates outliers while preserving the overall trend of the trajectory. This improves the predicted trajectory's visual smoothness and produces modest improvements in RMSE on all 3 axes. The Kalman filter further improves trajectory stability by incorporating a dynamic motion model, producing consistent position estimates and reducing measurement noise. However, both methods operate using forward-only processing and therefore cannot fully exploit the whole trajectory dataset. The best performance is achieved using the Rauch-Tung-Striebel smoother, which applies bidirectional state estimation. By utilizing both past and future measurements, the RTS smoother significantly reduces residual noise and improves the accuracy of trajectory reconstruction. The results show an overall improvement of approximately 8% in the RMSE compared to the raw UWB data, with the most significant decrease observed on the vertical axis. This demonstrates the effectiveness of offline smoothing techniques in compensating for measurement noise and geometric limitations in indoor UWB positioning systems.

This study provides a comprehensive experimental validation of a UWB indoor positioning system for UAV applications using high-precision VICON ground truth data. The work evaluates positioning accuracy, analyzes the impact of anchor geometry, and compares multiple offline filtering techniques to determine their effectiveness. The main personal contributions include the design and implementation of the experimental setup, the alignment and synchronization of the two positioning systems, the accuracy analysis of the UWB system based on RMSE metrics, and the comparative assessment of filtering strategies for trajectory refinement and evaluation of the achievable accuracy of the UWB system.

Overall, the results demonstrate that UWB positioning, when combined with appropriate filtering techniques, represents a viable solution for indoor UAV navigation in emergency scenarios, in GNSS-denied areas where drift-free localization is required.

Scientific Ethics Declaration

* The author declares that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the author.

Conflict of Interest

* The author declares that there is no conflict of interest.

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Author(s) Information

Ivănescu Georgiana-Florentina

Polytechnic University of Bucharest

Splaiul Independenței no. 313, Sector 6, 060042 Bucharest, Romania

*Contact e-mail: georgiana.ivanescu@stud.aero.pub.ro

ORCID iD: <https://orcid.org/0009-0007-3146-8983>

*Corresponding author(s) contact email

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A Truncated Spline Nonparametric Logistic Regression: Simultaneous Testing and Model Comparison

Afiqah Saffa Suriaslan

Sepuluh Nopember Institute of Technology

I Nyoman Budiantara

Sepuluh Nopember Institute of Technology

Vita Ratnasari

Sepuluh Nopember Institute of Technology

Dursun Aydin

Mugla Sıtkı Koçman University

Abstract: Regression is widely used in statistical analysis. For binary response variables, Logistic Regression has been widely applied due to its interpretability. However, conventional Binary Logistic Regression (BLR) generally assumes a linear relationship between predictors and the response, which may limit its ability to capture complex data patterns. To address this limitation, this study examines a Truncated Spline Nonparametric Logistic Regression (TSNLR) model that provides greater flexibility in modeling nonlinear relationships through the use of knot points. Statistical inference of the proposed model is examined using simultaneous hypothesis testing to assess the significance of predictor variables. The TSNLR model is applied to Human Development Index (HDI) data of cities/districts in Indonesia, which are classified into high and low HDI categories. Model performance is evaluated and compared with BLR using classification performance metrics. These findings suggest that TSNLR is an effective alternative for modeling binary response data with complex predictor relationships and can offer improved interpretability in applied statistical analysis.

Keywords: Truncated spline, Binary logistic, Simultaneous test, Human Development Index (HDI)

Introduction

Regression has become an analytical framework in statistical, enabling the prediction of outcomes and trends based on historical data (Yahya, 2022). Over the past few decades, regression analysis has significantly advanced from classical statistical approaches to more advanced methods (Joshi & Dhakal, 2021; Marasco et al., 2022). In the case of binary response variables that follow a Bernoulli distribution, binary logistic regression becomes one of the most widely used methods (Hosmer & Lemeshow, 2000). Through this approach, model parameter estimates can be obtained and used to explain the effect of predictor variables on the probability of an event occurring.

Various studies have examined binary logistic regression (Manoharan et al., 2020, Saifudin et al., 2024; Alfardus & Rawat, 2024) specially from the perspective of statistical inference, such as parameter hypothesis testing (Rusliyadi et al., 2021; Yuniarsih et al., 2024) and confidence interval formation (Gupta et al., 2020; Zhang et al., 2020). However, most of these studies in the field of binary logistic regression have only focused on the assumption of a linear relationship between predictor variables and logit functions, thereby limiting the flexibility of the model when faced with data with more complex patterns.

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In practice, the relationship between predictor and response variables is often nonlinear (Eubank, 1999). This condition has encouraged the development of nonparametric regression approaches that do not depend on specific function forms, such as truncated splines (Budiantara, 2005). This approach is considered more effective because this method works by dividing the predictor variable domain into several subintervals through knot points, so that changes in relationship patterns in each subinterval can be modeled more accurate (Hazelton & Turlach, 2011), (Permatasari et al., 2021). Further developments have led to the use of nonparametric approaches in binary logistic regression, including local likelihood approaches to logistic models (Suliyanto et al., 2020), Fourier series functions (Zulfadhli et al., 2025), and truncated spline function integration (Suriaslan, et al., 2025a, 2025b).

Based on previous studies, this article aims to develop a binary logistic regression model using a truncated spline approach and examine its statistical inference through simultaneous parameter significance testing. The proposed modeling framework is applied to data on the Human Development Index (HDI) of districts/cities in Indonesia in 2023, which are categorized into high and low HDI levels. Furthermore, the performance of the proposed method is compared with traditional binary logistic regression to evaluate improvements in modeling performance.

Method

The research methodology is presented using a workflow diagram, as shown in Figure 1.

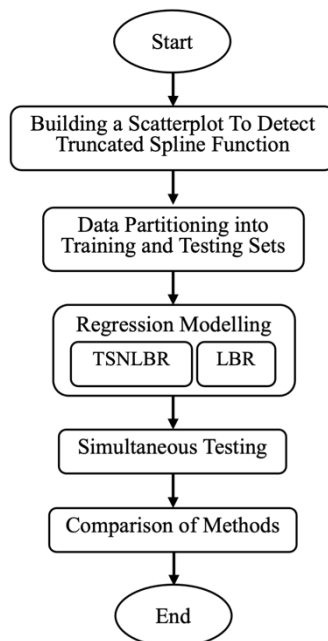


Figure. 1. Analysis workflow

Data Application

This study used secondary data obtained from the Indonesia Central Bureau of Statistics (BPS). The sample consists of 514 districts/cities in Indonesia for the year 2023, of which 305 are classified as having high HDI, while 209 are classified as having low HDI. The details of the variables are presented in Table I.

Table 1. Variable research

Variables	Description
	Human Development Index (HDI)
y	0 = Low HDI 1 = High HDI
v_1	Household access to clean water (%)
v_2	Poverty rate
v_3	Rate of open unemployment
v_4	High school participation rate

HDI modeling using the TSNBLR method begins by exploring the relationship between the logit of the response variable and the predictor variable. This exploration is presented in a scatter diagram in Fig. 2.

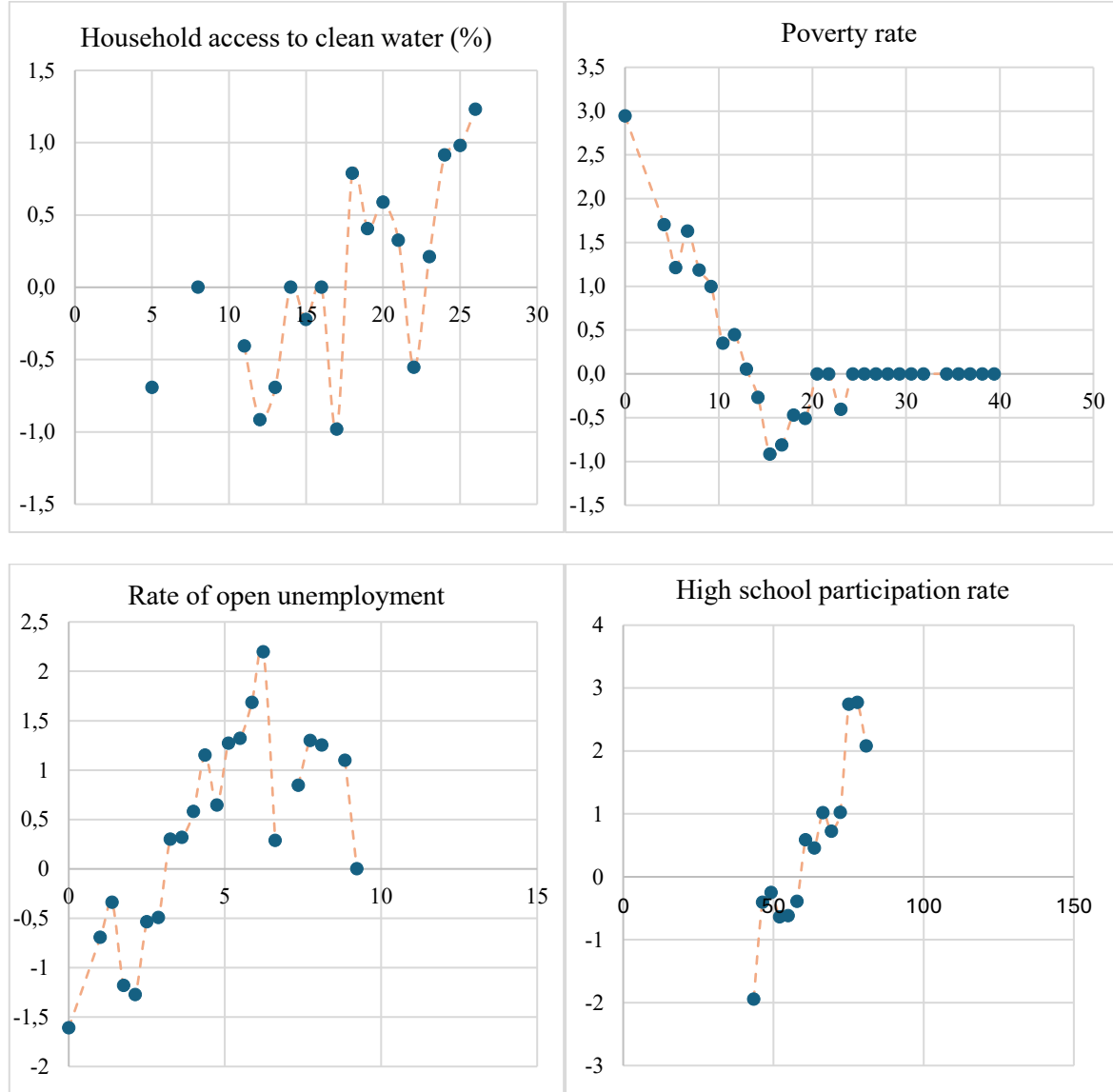


Figure 2. Scatterplots of the relationships between logit function of HDI and predictor variables

Based on the scatter plot in Fig. 2, it can be initially identified that there is a tendency for the relationship to fluctuate in certain sub-intervals. Therefore, in this study, it is appropriate to model the HDI using the Truncated Spline approach.

Binary Logistic Regression (BLR)

Agresti (2002) explains that the logistic regression model is expressed as $\pi(\mathbf{w}_i)$, where $\pi(\mathbf{w}_i)$ is defined as follows:

$$\pi(\mathbf{w}_i) = \frac{\exp(\beta_0 + \beta_1 w_{1i} + \beta_2 w_{2i} + \dots + \beta_p w_{pi})}{1 + \exp(\beta_0 + \beta_1 w_{1i} + \beta_2 w_{2i} + \dots + \beta_p w_{pi})} \quad (1)$$

The response variable in logistic regression is binary and will have a probability of $\pi(\mathbf{v}_i)$ if it is 1, and probability of $1 - \pi(\mathbf{v}_i)$ if it is 0.

Simultaneous tests can determine whether the regression model used in general has sufficient ability to explain the relationship between the response variable and the predictor variable. The hypotheses used in simultaneous tests are as follows:

$$H_0: \beta_1 = \beta_2 = \dots \beta_p = 0$$

$$H_1: \text{At least there is one } \beta_j \neq 0, j = 1, 2, \dots, p$$

The test statistics used based on the Likelihood Ratio Test (LRT) method are as follows (Hosmer & Lemeshow, 2000):

$$G^2 = 2[\ln l(\hat{\Omega}) - \ln l(\hat{\omega})] \quad (2)$$

Where

ω : set of parameters under H_0

Ω : set consisting of parameters under the population

The null hypothesis H_0 is rejected if the test statistic G^2 exceeds the chi-square critical value $\chi^2_{(\alpha, p)}$ or, equivalently, if the p - value is less than α . Rejection of H_0 indicates that at least one model parameter is statistically significant.

Truncated Spline Nonparametric Logistic Regression (TSNLR)

Given response variable (Y_i) is bernoulli distributed, and $v_{1i}, v_{2i}, \dots, v_{pi}; i = 1, 2, \dots, n$, are as many as p predictor variables. The probability distribution formulated as (Hosmer & Lemeshow, 2000):

$$P(Y_i = y_i) = \pi(v_i)^{y_i} (1 - \pi(v_i))^{1-y_i} \quad (3)$$

When (3) is formulated in exponential form, it belongs to the exponential family of distributions. The logit function is defined as:

$$\ln\left(\frac{\pi(v_i)}{1-\pi(v_i)}\right) = f(v_{1i}, v_{2i}, \dots, v_{3i}) \quad (4)$$

Then a logit transformation is performed to obtain a logistic regression model, is expressed as:

$$\ln(\exp f(v_{1i}, v_{2i}, \dots, v_{3i})) = \ln\left(\frac{\pi(v_i)}{1-\pi(v_i)}\right) \quad \pi(v_i) = \frac{\exp f(v_{1i}, v_{2i}, \dots, v_{3i})}{1 + \exp f(v_{1i}, v_{2i}, \dots, v_{3i})} \quad (5)$$

The function $f(v_{1i}, v_{2i}, \dots, v_{3i})$ in (5) is approximated by a truncated spline function with knot points $K_{1j}, K_{2j}, \dots, K_{pj}$, where j is 1, 2, ..., p . Consequently, the TSNBLR model can be expressed as (Suriaslan, et al., 2025a):

$$\pi(v_i) = \frac{\exp(\sum_{j=1}^p \sum_{k=0}^m \gamma_{jk} v_{ji}^k + \sum_{j=1}^p \sum_{u=1}^r \gamma_{j(m+u)} (v_{ji} - K_{ju})_+^m)}{1 + \exp(\sum_{j=1}^p \sum_{k=0}^m \gamma_{jk} v_{ji}^k + \sum_{j=1}^p \sum_{u=1}^r \gamma_{j(m+u)} (v_{ji} - K_{ju})_+^m)} \quad (6)$$

where, γ_0, γ_{jk} , and $\gamma_{j(m+u)}, j = 1, 2, \dots, p, k = 1, 2, \dots, m, u = 1, 2, \dots, r$ are the model parameters in the truncated spline function. Truncated function for spline is represented by the following equation:

$$(v_{ji} - K_{ju})_+^m = \begin{cases} (v_{ji} - K_{ju})^m, & v_{ji} \geq K_{ju} \\ 0, & v_{ji} < K_{ju} \end{cases} \quad (7)$$

The simultaneous test evaluates the significance of the full set of model parameters γ in the model, with hypothesis:

$$H_0: \gamma_0 = \gamma_{11} = \dots = \gamma_{p1} = \dots = \gamma_{p(m+r)} = 0$$

$$H_1: \text{at least one } \gamma_{jk} \neq 0 \text{ or } \gamma_{j(m+u)} \neq 0, j = 1, 2, \dots, p, k = 1, 2, \dots, (m + u), u = 1, 2, \dots, r$$

The test statistic used is the Likelihood Ratio Test (LRT), is formulated as (Suriaslan, et al., 2025b):

$$G^2 = 2[\ln l(\hat{\boldsymbol{\gamma}}_{\Omega}) - \ln l(\boldsymbol{\gamma}_{\omega})] - 2[\ln l(\hat{\boldsymbol{\gamma}}_{\omega}) - \ln l(\boldsymbol{\gamma}_{\omega})] \quad (8)$$

Equation (8) is approximated by a second-order Taylor series expansion around the MLE under the full model $\hat{\boldsymbol{\gamma}}_{\Omega}$

$$\ln l(\boldsymbol{\gamma}_{\omega}) \approx \ln l(\hat{\boldsymbol{\gamma}}_{\Omega}) + g(\hat{\boldsymbol{\gamma}}_{\Omega})(\boldsymbol{\gamma}_{\omega} - \hat{\boldsymbol{\gamma}}_{\Omega}) - \frac{1}{2}(\boldsymbol{\gamma}_{\omega} - \hat{\boldsymbol{\gamma}}_{\Omega})^T [I(\hat{\boldsymbol{\gamma}}_{\Omega})](\boldsymbol{\gamma}_{\omega} - \hat{\boldsymbol{\gamma}}_{\Omega}) \quad (9)$$

Because $g(\hat{\boldsymbol{\gamma}}_{\Omega})$ is zero in (9), it can be expressed as follows:

$$2[\ln l(\hat{\boldsymbol{\gamma}}_{\Omega}) - \ln l(\boldsymbol{\gamma}_{\omega})] \approx (\hat{\boldsymbol{\gamma}}_{\Omega} - \boldsymbol{\gamma}_{\omega})^T - [I(\hat{\boldsymbol{\gamma}}_{\Omega})](\hat{\boldsymbol{\gamma}}_{\Omega} - \boldsymbol{\gamma}_{\omega}) \quad (10)$$

The ln-likelihood function $\ln l(\boldsymbol{\gamma}_{\omega})$ expanding around $\hat{\boldsymbol{\gamma}}_{\omega}$ gives:

$$\ln l(\boldsymbol{\gamma}_{\omega}) \approx \ln l(\hat{\boldsymbol{\gamma}}_{\omega}) + g(\hat{\boldsymbol{\gamma}}_{\omega})(\boldsymbol{\gamma}_{\omega} - \hat{\boldsymbol{\gamma}}_{\omega}) - \frac{1}{2}(\boldsymbol{\gamma}_{\omega} - \hat{\boldsymbol{\gamma}}_{\omega})^T [I(\hat{\boldsymbol{\gamma}}_{\omega})](\boldsymbol{\gamma}_{\omega} - \hat{\boldsymbol{\gamma}}_{\omega}) \quad (11)$$

As $g(\hat{\boldsymbol{\gamma}}_{\omega})$ is zero in (11), it may be defined as follows:

$$2[\ln l(\hat{\boldsymbol{\gamma}}_{\omega}) - \ln l(\boldsymbol{\gamma}_{\omega})] \approx (\hat{\boldsymbol{\gamma}}_{\omega} - \boldsymbol{\gamma}_{\omega})^T [I(\hat{\boldsymbol{\gamma}}_{\omega})] - (\hat{\boldsymbol{\gamma}}_{\omega} - \boldsymbol{\gamma}_{\omega}) \quad (12)$$

Based on (10) and (11), the LRT statistic becomes:

$$G^2 \approx (\hat{\boldsymbol{\gamma}}_{\Omega} - \boldsymbol{\gamma}_{\omega})^T [I(\boldsymbol{\gamma}_{\Omega})](\hat{\boldsymbol{\gamma}}_{\Omega} - \boldsymbol{\gamma}_{\omega}) - (\hat{\boldsymbol{\gamma}}_{\omega} - \boldsymbol{\gamma}_{\omega})^T [I(\hat{\boldsymbol{\gamma}}_{\omega})](\hat{\boldsymbol{\gamma}}_{\omega} - \boldsymbol{\gamma}_{\omega}) \quad (13)$$

Based on (Pawitan, 2001), the maximum likelihood estimator $\hat{\boldsymbol{\gamma}}_{\Omega}$ satisfies the asymptotic distribution:

$$(\hat{\boldsymbol{\gamma}}_{\Omega} - \boldsymbol{\gamma}_{\Omega}) \xrightarrow{d} N(\mathbf{0}, [I(\hat{\boldsymbol{\gamma}}_{\Omega})]^{-1})$$

where,

$$I(\hat{\boldsymbol{\gamma}}_{\Omega}) = \begin{bmatrix} [I_{11}] & [I_{12}] \\ [I_{21}] & [I_{22}] \end{bmatrix}$$

The quadratic form $(\hat{\boldsymbol{\gamma}}_{\Omega} - \boldsymbol{\gamma}_{\omega})^T [I(\hat{\boldsymbol{\gamma}}_{\Omega})](\hat{\boldsymbol{\gamma}}_{\Omega} - \boldsymbol{\gamma}_{\omega})$ in (13) can be decomposed into:

$$(\hat{\boldsymbol{\gamma}}_{\Omega} - \boldsymbol{\gamma}_{\omega})^T [I(\hat{\boldsymbol{\gamma}}_{\Omega})](\hat{\boldsymbol{\gamma}}_{\Omega} - \boldsymbol{\gamma}_{\omega}) = \begin{bmatrix} \hat{\boldsymbol{\gamma}}_1 \\ \hat{\boldsymbol{\gamma}}_2 - \boldsymbol{\gamma}_{0\omega} \end{bmatrix}^T \begin{bmatrix} [I_{11}] & [I_{12}] \\ [I_{21}] & [I_{22}] \end{bmatrix} \begin{bmatrix} \hat{\boldsymbol{\gamma}}_1 \\ \hat{\boldsymbol{\gamma}}_2 - \boldsymbol{\gamma}_{0\omega} \end{bmatrix} \quad (14)$$

thus obtained:

$$G^2 \approx \hat{\boldsymbol{\gamma}}_1^T ([I_{11}] - [I_{12}][I_{22}]^{-1}[I_{21}])\hat{\boldsymbol{\gamma}}_1 \quad (15)$$

Equation (15) is simplified to

$$G^2 \approx \hat{\boldsymbol{\gamma}}_1^T [I^{11}]^{-1}\boldsymbol{\gamma}_1 \quad (16)$$

where,

$$\hat{\boldsymbol{\gamma}}_1 \xrightarrow{d} N\left(\mathbf{0}, [I^{11}]_{(p(m+r) \times p(m+r))}\right), \text{ and } [I^{11}]^{-\frac{1}{2}}\hat{\boldsymbol{\gamma}}_1 \xrightarrow{d} N\left(\mathbf{0}, I_{(p(m+r) \times p(m+r))}\right)$$

Assuming the null hypothesis H_0 is true, the LRT statistic converges asymptotically to a chi-square distribution with $p(m+r)$ degrees of freedom.

$$G^2 \approx \left[[I^{11}]^{-\frac{1}{2}}\hat{\boldsymbol{\gamma}}_1 \right]^T \left[[I^{11}]^{-\frac{1}{2}}\boldsymbol{\gamma}_1 \right] \approx Z^T Z \xrightarrow{d} \chi_{p(m+r)}^2$$

Thus it can be concluded $G^2 \xrightarrow{d} \chi_{p(m+r)}^2$

For simultaneous testing of model parameters, the rejection region of the null hypothesis H_0 at significance level α is defined according to the distribution of the test statistic, expressed as:

$$G^2 > \chi^2_{(\alpha, p(m+r))}$$

Results and Discussion

The dataset is divided into training and testing sets with an 80:20 ratio, where the training data are used for model estimation and parameter inference, while the testing data are employed to evaluate predictive performance. Modeling was performed considering all combinations of predictor variables and knot points. The best model selection was determined based on the minimum Akaike Information Criterion (AIC) value. The TSNBLR results showed that the best model was obtained when all four predictor variables were included in the model with the optimal knot point combination, are $K_{1u} = 1$, $K_{2u} = 1$, $K_{3u} = 1$, and $K_{4u} = 4$, as presented in Table 2.

Table 2. TSNLR Number Of Knots

No.	Number of Knot	AIC
1	1, 1, 1, 1	427.67
2	2, 1, 1, 1	429.60
3	3, 1, 1, 1	429.83
4	4, 1, 1, 1	431.30
	⋮	
193	1, 1, 1, 4	423.67
194	2, 1, 1, 4	425.56
	⋮	
255	3, 4, 4, 4	435.20
256	4, 4, 4, 4	436.45

Based on the Table 2, it can be seen that the optimal knot point model are $K_{11} = 90.27$, $K_{21} = 9.62$, $K_{31} = 4.02$, $K_{41} = 58.96$, $K_{42} = 62.81$, $K_{43} = 64.76$, and $K_{44} = 67.64$.

Table 3. Parameter Estimation Of TSNLR

Parameter	Estimation	Parameter	Estimation
$\hat{\gamma}_0$	-7.869	$\hat{\gamma}_{32}$	-0.830
$\hat{\gamma}_{11}$	0.040	$\hat{\gamma}_{41}$	0.066
$\hat{\gamma}_{12}$	-0.017	$\hat{\gamma}_{42}$	-0.082
$\hat{\gamma}_{21}$	-0.197	$\hat{\gamma}_{43}$	1.113
$\hat{\gamma}_{22}$	-0.058	$\hat{\gamma}_{44}$	-1.618
$\hat{\gamma}_{31}$	0.832	$\hat{\gamma}_{45}$	0.744

Based on the results of the TSNLR parameter obtained in Table, the model for HDI can be written in the following equation:

$$\text{Logit } \pi(v_i) = -7.869 + 0.040v_{1i} - 0.017(v_{1i} - 90.27) - 0.197v_{2i} - 0.058(v_{2i} - 9.62)_+ + 0.832v_{3i} - 0.830(v_{3i} - 4.02)_+ + 0.066v_{4i} - 0.082(v_{4i} - 58.96)_+ + 1.113(v_{4i} - 62.81)_+ - 1.618(v_{4i} - 64.76)_+ + 0.744(v_{4i} - 67.64)_+$$

Table 4. Simultaneous Test Of TSNLR

Test Statistic	Value
G^2	292.494
χ^2	19.675
$p\text{-value}$	3.337e-56

Based on the Simultaneous Hypothesis Test Results, the test statistic value G^2 is 292.494 with a p-value of 3.337×10^{-56} . Meanwhile, from the chi-square distribution table, the critical value $\chi^2_{(0.005;11)} = 19.675$ was obtained. Because the G^2 value is greater than the $\chi^2_{(0.005;11)}$ value, or equivalently p-value < 0.05 , the null hypothesis is

rejected. Thus, it can be concluded that there is at least one predictor variable that has a significant effect on the HDI.

As material for model evaluation, at this stage a conventional binary logistic regression model is constructed.

Table 5. Parameter Estimation Of BLR

Parameter	Estimation
$\hat{\beta}_0$	-7.959
$\hat{\beta}_1$	0.037
$\hat{\beta}_2$	-0.228
$\hat{\beta}_3$	0.278
$\hat{\beta}_4$	0.106

Based on the results of the BLR parameter obtained in Table, the model for HDI can be written in the following equation:

$$\text{logit}(\pi(x_i)) = -7.959 + 0.0375x_{1i} - 0.228x_{2i} + 0.278x_{3i} + 0.106x_{4i}$$

Table 6. Simultaneous Test Of BLR

Test Statistic	Value
G^2	271.489
χ^2	9.488
$p\text{-value}$	1.523e-57

Based on the simultaneous hypothesis test, the test statistic G^2 is 271.489 with a p-value of 1.523×10^{-57} . Since G^2 exceeds the critical value $\chi^2_{(0.005, 11)} = 9.488$, or equivalently the p-value is less than 0.05, the null hypothesis is rejected. This indicates that at least one predictor variable has a significant effect on HDI.

Table 7. Comparison of Models

Test Statistic	TSNLR	BLR
Accuracy	82.9%	81.1%
Sensitivity	88%	87.7%
Specificity	75.2%	73.3%
Precision	84.1%	83.1%
F1	86.03%	85.3%
AUC	89.5%	88.4%

Based on the results of testing on the test data, TSNLR showed better classification performance than binary logistic regression. TSNLR produced an accuracy of 82.9%, higher than the logistic model at 81.1%. The sensitivity of TSNLR models is 88%, which is higher than BLR and shows ability in identifying areas with high HDI categories. However, the specificity of TSNLBR is higher, at 75.2% compared to 73.3% for BLR, so TSNLBR is better at recognizing areas with low HDI. In addition, the precision and F1-score values of TSNLBR are 84.1% and 86.03%, respectively, which are higher than those of the BLR model. However, the AUC value of TSNLR is slightly higher, at 89.5% compared to 88.4% for TSNBLR, indicating that TSNLR has slightly better discrimination capabilities at various classification thresholds. Overall, TSNLR showed better classification performance than BLR on most evaluation metrics.

Conclusion

This study shows that Truncated Spline Nonparametric Logistic Regression (TSNLR) is an effective methodological approach in modeling the Human Development Index (HDI), especially when the relationship between predictor and response variables is change in certain subinterval. The selection of the optimal knot point combination based on the AIC criterion produces a statistically significant model that is capable of improving classification performance compared to conventional Binary Logistic Regression (BLR), particularly in terms of accuracy, specificity, precision, and F1-score. Although the difference in AUC values between the two models is relatively small, the overall evaluation results confirm that the TSNLR approach provides better modeling flexibility without sacrificing discrimination ability, thus contributing as a competitive and relevant methodological alternative in the analysis of binary response data with complex relationship patterns.

Recommendations

Building on the current findings, future research may extend the TSNLR by considering higher order spline functions, such as quadratic or cubic forms. In addition, incorporating spatial data settings could be explored to better capture regional interdependencies. Further extensions may also involve semiparametric modeling to allow flexible relationships between the variables.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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Author(s) Information

Afiqah Saffa Suriaslan

Sepuluh Nopember Institute of Technology
Kampus ITS- Sukolilo, Surabaya 60111, Indonesia
ORCID iD: <https://orcid.org/0009-0001-8176-1527>

I Nyoman Budiantara

Sepuluh Nopember Institute of Technology
Kampus ITS- Sukolilo, Surabaya 60111, Indonesia
ORCID iD: <https://orcid.org/0000-0001-6572-4083>
*Contact e-mail: i_nyoman_b@statistika.its.ac.id

Vita Ratnasari

Sepuluh Nopember Institute of Technology
Kampus ITS- Sukolilo, Surabaya 60111, Indonesia
ORCID iD: <https://orcid.org/0000-0002-7579-4752>

Dursun Aydin

Mugla Sıtkı Kocman University
48000 Mentese/Mugla, Türkiye
ORCID iD: <https://orcid.org/0000-0001-8393-1270>

*Corresponding author(s) contact email

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Analysis of MEMS IMU Errors Impact on UAV Positioning Accuracy

Antofie Bianca-Gabriela

Polytechnic University of Bucharest

Abstract: This paper proposes a comprehensive study conducted over one of the primary sources of positioning errors in unmanned aerial systems (UAVs) navigation systems: the inherent limitations of embedded miniaturized inertial measurement units (IMUs). In recent years, MEMS technologies have come to dominate the electronics market due to their promising advantages of reduced cost and size, low power consumption and series production. These aspects make them particularly attractive for the applications in which compactness and autonomy are critical, such as in the UAV industry. However, the drawbacks of MEMS devices are their susceptibility to environmental factors and their intrinsic imperfection which result in errors and noises contaminating the output acceleration and angular velocity signals. Improper sensing of vehicle dynamics may consequently lead to erroneous computation within the strap-down navigation algorithm. For this reason, errors and noises originating from the inertial subsystem may substantially degrade the precision of the final global coordinates and compromise the overall mission success. The current research aims to provide a clear examination of the aspects influenced by IMU errors throughout the navigation algorithm, as well as to identify potential approaches for further research in the field of positioning accuracy enhancement.

Keywords: UAV navigation systems, Miniaturized inertial measurement units, Strap-down navigation algorithm, IMU errors, Positioning accuracy enhancement

Introduction

In the context of autonomous systems emergence, aerospace manufacturers place significant emphasis on the development of compact avionics, lightweight design, continuous monitoring of operational parameters and successful mission fulfillment. From this perspective, MEMS (Micro-Electro Mechanical Systems) technology has gained popularity in the aerospace sector because it promises to provide key features such as reduced dimension and power consumption, low production costs, while maintaining an optimal performance. (Osiander, 2006)

Unmanned Aerial Vehicles (UAVs) or more familiar drones, represent the future for numerous military and civil applications due to the reduced human life risk, full autonomy and enhanced mission flexibility involved. The overall operational behavior of any UAV depends on its capability to maintain stable flight control while executing mission commands either on manual or autopilot mode, functions ensured by its primary component: the navigation system. Modern drones include at least two complementary navigation systems, among which the Global Navigation Satellite System (GNSS), the Inertial Navigation System (INS), radio navigation system and image-based navigation system are the most commonly used (Bekir, 2007; Zhang, 2025).

Satellite navigation represents the main source of navigation data due to its global coverage and long-term accuracy; however, in areas where the signal is jammed or obstructed, at least one secondary system is needed. For instance, the inertial system maintains positioning continuity by virtue of its independence from external factors and superior short-term precision (Grewal, 2020). Radio beacons are also a suitable choice for integration with GPS due to their positioning accuracy on the order of tens of meters. Nevertheless, their performance is highly dependent on the line-of-sight specification of the drone (Arning, 2007). In image-based

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navigation, the main concept refers to mapping the area surrounding the UAV through image processing techniques and returning its location, relative position and attitude, as well as providing obstacle detection capabilities and visual warnings to the operator (Liao, 2021).

In view of technological advancements over the last decades, nowadays inertial navigation systems come in strap-down architectures in which inertial sensors directly measure the motion of the vehicle to which they are rigidly attached to and combined into an inertial measurement unit (IMU). Moreover, they incorporate a variety of technologies depending on the precision requirements of the application and associated financial constraints; however, MEMS sensors appear to dominate the sensor market compared to other alternative existing solutions.

As a matter of fact, microelectronics rose as a result of the increased interest of researchers in silicon, a material that has proven to possess ideal mechanical and thermal properties for semiconductor fabrication. By means of micromachining techniques, microsystems with sensing or actuation functions have been successfully integrated into micro- and nano-scale chips, thus giving rise to MEMS and NEMS technologies (Choudhary, 2013).

For design reasons, the majority of UAV systems include miniaturized IMUs, typically from mass production provenience. Consequently, the main interest of most producers is on the rapid, large-scale fabrication while preserving the low cost and size, rather than the quality of the product. Factors such as manufacturing imperfections, limitations associated with miniaturization processes and insufficient serial testing significantly affect the precision of these sensors (Liu, 2025).

The sensitive precision of miniaturized IMUs can generate considerable positioning errors and may negatively affect flight control tasks, even if other navigation systems are being used on the respective UAV. Thus, it is essential to understand how these errors influence positioning accuracy, by studying their behavior not only under static conditions, but also in complex dynamic environments (Amirsadri, 2012).

This paper aims to provide an analysis of the main error types specific to MEMS-based IMUs through a two-stage approach. The first part focuses on the identification and characterization of errors by using a simulated sensor model, while the second section evaluates their influence in a real flight scenario, on an integrated INS/GPS navigation system resembling modern architecture.

Overview of MEMS-based Inertial Measurement Units

IMU Architecture Description

An IMU mainly consists of an assembly of inertial sensors - a triad of accelerometers and a triad of gyroscopes - which are incapsulated together in a small chip using micromachining techniques. In inertial navigation systems, IMU provides the measurements of specific forces (which are later corrected with the gravitational acceleration to obtain raw linear accelerations) and angular velocity necessary for further conversion throughout the strap-down navigation algorithm (Titterton, 2005; Grewal, 2020) .

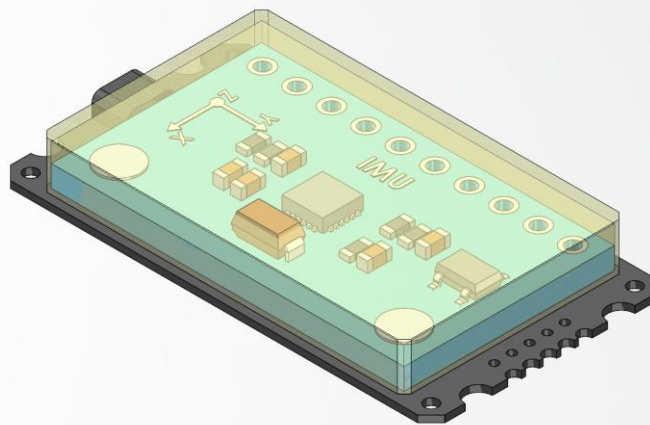


Figure 1. Inertial Measurement Unit packaging

In aerospace applications, these sensors are commonly fabricated in three-axis configurations, maximizing space and simplifying algorithm implementation. Besides accelerometers and gyroscopes, an IMU contains magnetometers, temperature and pressure sensors, a microcontroller, signal processing electronics, a power supply port and output protocols. (TDK Electronics)

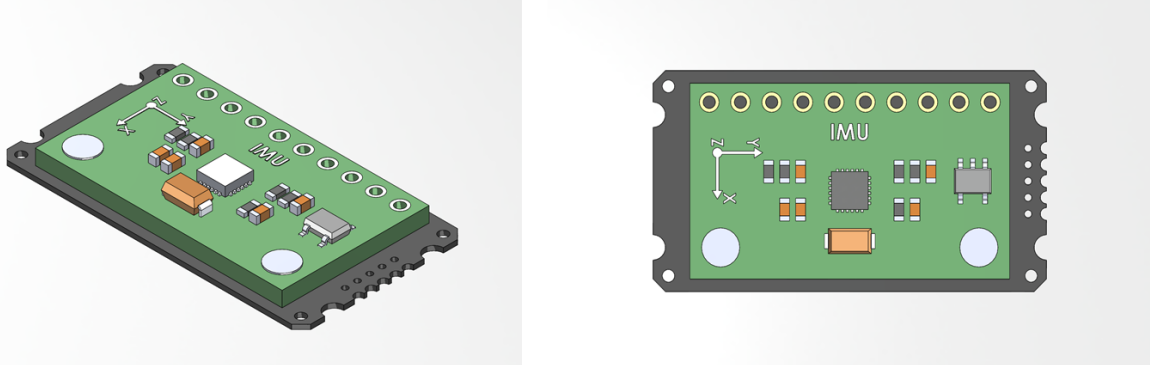


Figure 2. Inertial Measurement Unit PCB layout

The precision class of the IMU defines the scale of the fabrication constraints, therefore, the lower the price, the lower quality of materials, attention to details and time assigned for the respective component. To support sensor performance, there comes interest for research in the areas of error modelling and compensation, signal processing and advanced filtration methods, as well as positioning accuracy enhancement.

Classification of Specific Errors and Noises

MEMS-based inertial sensors generally present two main categories of errors in their output signals, *deterministic* and *stochastic* errors, which tend to accumulate over time if not eliminated and dramatically influence the overall accuracy of the inertial navigator. Both categories of errors are influenced by internal and external factors, including manufacturing imperfections, environmental conditions, mechanical vibrations or shocks and electromagnetic interference. Therefore, an IMU error model should be defined from the earliest stage of system development.

The mathematical equation describing the relation between the input measurements $f(t)$ and $\omega(t)$ and the output signals of the IMU inertial sensors $\tilde{f}(t)$ and $\tilde{\omega}(t)$ can be expressed as (Farrell, 2021):

$$\begin{cases} \tilde{f}(t) = f(t) + d_{acc}(\vec{f}(t)) + s_{acc}(t) \\ \tilde{\omega}(t) = \omega(t) + d_{gyro}(\vec{\omega}(t)) + s_{gyro}(t) \end{cases} \quad (1)$$

where $d_{acc}(\vec{f}(t)), d_{gyro}(\vec{\omega}(t))$ - deterministic errors of vector measurements $\vec{f}, \vec{\omega}$; s_{acc}, s_{gyro} - stochastic errors.

Deterministic Errors

Deterministic errors, such as biases, scale factors or axis misalignment errors can be determined and eliminated through calibration or compensation algorithms.

In the case of accelerometers, the calibration procedure involves using a mechanical platform for static tests of different positions of the chip, while for gyroscopes, different angle rates are being studied. The sensors are recalibrated when employed on UAVs using similar simple procedures. As a result, IMU sensors datasheet parameters are determined for static states and they may differ considerably in dynamic scenarios depending on the class of precision of the IMU. For tactical IMUs, calibration tests are performed for each unit individually for an appropriate interval of time, while in the commercial category, the emphasis is on high quantity in the shortest amount of time.

Equation (2) illustrates the error model associated to the IMU (Titterton, 2005; El-Diasty, 2008):

$$\begin{cases} \tilde{f} = (1 + SF_f + M_f)\omega + B_f + v_f \\ \tilde{\omega} = (1 + SF_\omega + M_\omega)\omega + G_\omega a + B_\omega + v_\omega \end{cases}, \quad (2)$$

where: SF_f, SF_ω - scale factor errors; M_f, M_ω - misalignment matrices; G_ω - g-sensitivity matrix; B_f, B_ω - biases; v_f, v_ω - stochastic errors (noises).

Bias is generally defined as the output of the sensor when no force is applied at the input. IMUs present both accelerometer and gyro biases in their static states. Bias error divides itself in turn into a first deterministic part, the systematic offset, and a second random part, the time-varying offset which cannot be predicted over time. Constant bias is experimentally determined in testing phases, with typical accelerometer values starting from $10^{-3}g$ to even $10^{-6}g$, while values for gyroscopes generally range from 10^{-5} to 10^{-1} $^\circ/s$. (Ailneni, 2019)

Scale factor represents the ratio between the output signal and the physical quantity acting along the sensitivity axis of the sensor. The ideal scale factor is 1; however, the error of the calculated value based on the real sensor measurements is different from 1 and this difference is called the scale factor error. General values are placed between 0.01% and 2% for accelerometers and gyroscopes.

Axis misalignment error is a direct consequence of the imperfect component mounting inside the sensor housing. It occurs when the inertial sensors' sensitivity axes are not perfectly orthogonal to one another. Similarly to bias, scale factor and axis misalignment errors can be determined in laboratory tests and are usually eliminated through calibration or compensation algorithms. Their values are situated in the 0.01° - 2° interval.

Another deterministic error, specific to gyroscopes, is the *g-sensitivity*, which roots back to their basic functioning principle - mechanical vibration. As a result, linear accelerations may create a false rotational movement and induce erroneous rotational velocity components to the output signal. General values range from $0.1^\circ/h/g$ to $10^\circ/h/g$ (Luu, 2007).

Figure 3 depicts the deterministic errors specific to MEMS IMUs.

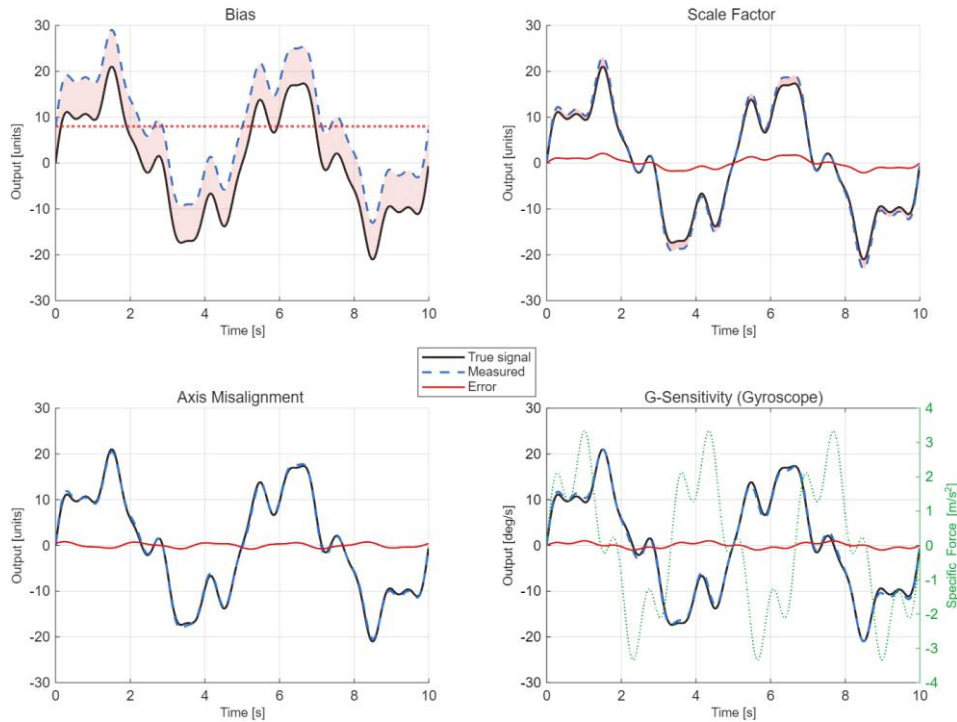


Figure 3. Deterministic errors of MEMS IMUs

Stochastic Errors

In contrast, *stochastic errors* or *noises* represent random processes resulted from unpredictable bias drifts over time or from inherent sensor noise. Unlike deterministic errors, they do not follow a certain path and tend to overlap the good signal, as they vary each time the sensor is powered on. For this reason, these errors must be modelled by identifying the characteristics specific to stochastic processes and correlating them with time over long sampling intervals. The most widely used methods for stochastic error compensation include the Allan variance method, Gauss-Markov models, random state-space error models and other autocorrelation-based techniques (Grigorie, 2010; Farrell, 2022).

Stochastic errors consist of both low-frequency components-such as bias instability and rate random walk-and high frequency components, commonly referred to as noises.

Bias instability, or flicker noise, represents a low-frequency random drift in the sensor output signal and is typically modelled through a random walk or Gauss-Markov model.

Quantization noise is specific to sensors, being produced through analog-to-digital conversion included in the IMU circuitry. It resides in the difference between the amplitude of the sampled points and digital resolution of the ADC (Luu, 2007).

White noise represents the main source of stochastic error in an IMU and it is generally characterized by the noise density parameter. For accelerometers, the corresponding error is the velocity random walk (VRW), whereas for gyroscopes it is defined as angle random walk (ARW). These metrics indicate how measurement noise propagates and accumulates over time, ultimately leading to velocity and orientation accuracy degradation (Hussen, 2015).

Rate random walk (RRW) is derived from white noise and represents the progressive accumulation of noise over time, which results in long-term drift in the measured data.

Figure 4 depicts a graphical representation of the stochastic errors of MEMS-based IMUs.

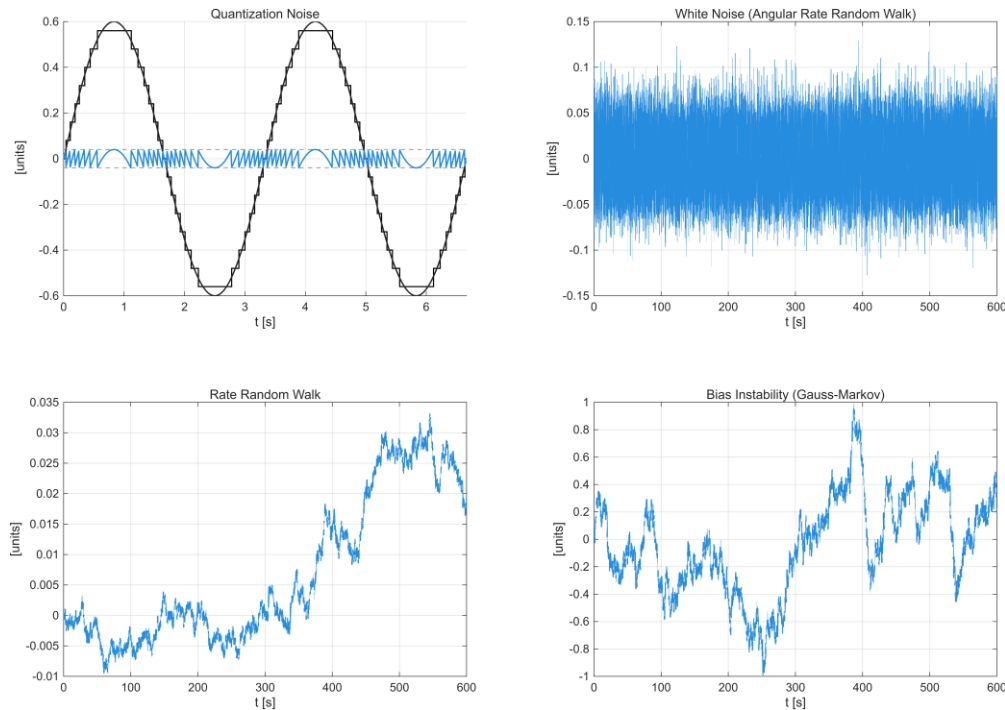


Figure 4. Stochastic errors of MEMS IMUs

Identification and Representation of IMU Errors

For the graphic illustration of the errors previously described, an IMU model developed from IEEE standard models for accelerometers and gyroscopes was implemented in MATLAB/Simulink, as shown in Figure 5. (Grigorie 2005, 2010)

The Analog Devices sensor ADIS16495 was selected for configuring the IMU model. ADIS16495 datasheet error parameters were included in Table 1. (Analog Devices Inc.)

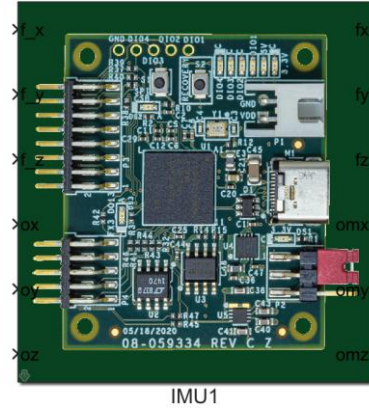


Figure 5. IMU model implemented in MATLAB/Simulink (Analog Devices Inc.)

Table 1. ADIS16495 datasheet specifications

Parameter	Gyroscope	Accelerometer
Bias	0.8 °/h	3.2μg
Scale Factor Error	±0.2%	±0.01%
Misalignment Error	±0.05°	±0.035°
G-sensitivity	0.006-0.015°/s	-
ARW/VRW	0.09°/√h	0.008 m/s/√h
Noise density	0.002°/sec/√Hz	17 μg/√Hz

In order to simulate the deterministic errors, a static condition was maintained for a simulation time of 60 seconds, with the following input values: $a_x=a_y=0$ m/s², $a_z=-9.80665$ m/s², $om_x=om_y=om_z=0$ °/s.

Figure 6 presents the corresponding output signals.

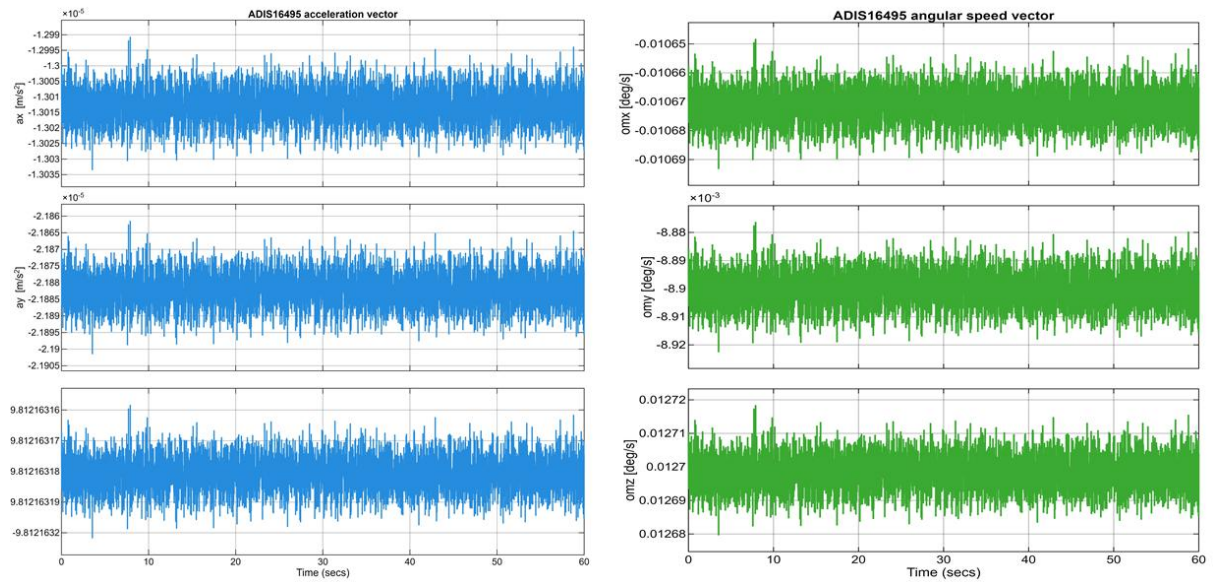


Figure 6. ADIS16495 simulated signals

The mean values of a_x and a_y returned were $-1.3013e-05$ m/s² and $-2.1882e-05$ m/s², respectively. As expected in a static condition, the values are very small and close to zero. According to the sensor datasheet, the expected bias is equal to $3 \cdot 10^{-4}$, a value that is consistent with the obtained results. The residual low values are produced by the bias and low-frequency stochastic errors.

The mean value of a_z , -9.8122 m/s^2 corresponds to a deviation of -0.0055 m/s^2 from the input value of gravitational acceleration (9.80665 m/s^2), which suggests the presence of a scale factor error of approximately 0.05% - slightly higher than the $\pm 0.01\%$ specified in the datasheet, but still acceptable for short-term measurements. For the angular speed measurements, the mean values were found to be $-0.0107 \text{ }^\circ/\text{s}$, $-0.0089 \text{ }^\circ/\text{s}$, $0.0127 \text{ }^\circ/\text{s}$. These results are close to the datasheet value for the gyroscope bias, 0.0002 (0.013 for the simulation time used), confirming the proper implementation of the sensor and the inferior performance of the gyroscope. This demonstrates that the gyroscope model may accumulate a notable amount of bias over longer intervals of time. However, in both cases the signal is visibly perturbed with stochastic errors, which can pose significant challenges for integration within the navigation algorithm due to the presence of low and high false frequency components.

For the analysis of stochastic errors, the statistical method of Allan Variance was used. The method works by dividing the signal into time intervals (or clusters) that are multiple of the sample rate and computing the average of the data within each interval (Grigorie, 2010). Allan Variance implies the calculation of differences between consecutive cluster averages and determining the variance of these differences for each interval length. Then, the log graph of the Allan Variance square root (Allan Deviation) against the cluster time τ gives the characteristic curve that represents the stochastic errors in the signal (Grigorie, 2012).

In the Allan Deviation plot, each stochastic error follows a particular linear trend, characterized by a specific slope. A slope of -1 corresponds to the quantization noise, a slope of -1/2 indicates white noise, a zero slope is associated with bias instability, while a +1/2 slope characterizes rate or acceleration random walk (Zhao, 2011). For the current case, only the bias instability, white noise and rate random walk have been considered.

Figure 7 depicts the Allan Deviation graph for the IMU simulated signals. As observed, the stochastic trend of the curves can be easily identified from their corresponding slopes.

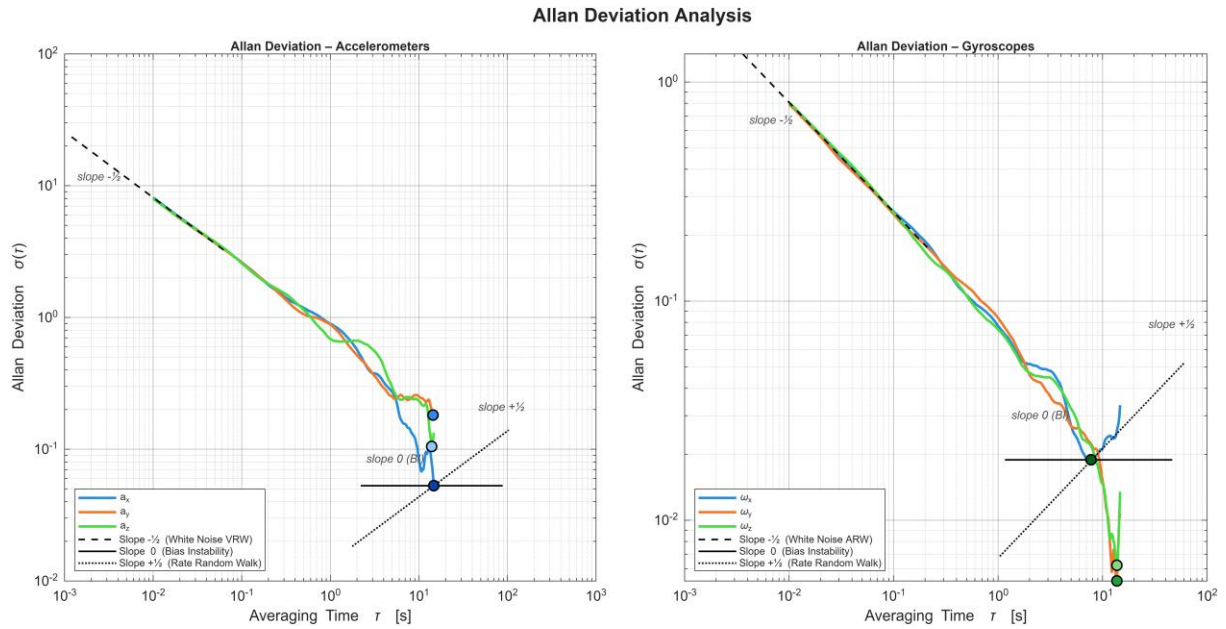


Figure 7. Allan Deviation Analysis of ADIS16495 signals

For the accelerometer, the white noise (VRW) can be identified through the -1/2 slope and is more pronounced at short averaging times ($\tau < 1\text{s}$). The measured white noise error magnitudes for the acceleration signals are: $a_x \approx 0.8125 \text{ m/s}^2$, $a_y \approx 0.6439 \text{ m/s}^2$, $a_z \approx 0.7946 \text{ m/s}^2$. Bias instability is indicated by the 0 slope, with the corresponding values: $a_x \approx 0.0528 \text{ m/s}^2$, $a_y \approx 0.1815 \text{ m/s}^2$, $a_z \approx 0.1049 \text{ m/s}^2$. Since a_y exhibits the largest bias instability, this may result in more drift on y axis over long-term measurements. The acceleration random walk is visible on slope +1/2 and becomes dominant at large averaging times, with the following values: $a_x \approx 0.0238 \text{ m/s}^2$, $a_y \approx 0.0904 \text{ m/s}^2$, $a_z \approx 0.0491 \text{ m/s}^2$.

Regarding the gyroscopes, white noise is evident at short averaging times ($\tau < 0.1\text{s}$), with measured values of $\omega_x \approx 0.0806 \text{ }^\circ/\text{s}$, $\omega_y \approx 0.0644 \text{ }^\circ/\text{s}$, $\omega_z \approx 0.0726 \text{ }^\circ/\text{s}$. Bias instability values are: $\omega_x \approx 0.0189 \text{ }^\circ/\text{s}$, $\omega_y \approx 0.0052 \text{ }^\circ/\text{s}$, $\omega_z \approx 0.0062 \text{ }^\circ/\text{s}$, indicating that y and z axes are more stable than the x axis in this sensor model. Finally, rate

random walk manifests as an upward slope at high τ , suggesting the accumulation of drift over time. The corresponding values are: $\text{om}_x \approx 0.0116^\circ/\text{s}$, $\text{om}_y \approx 0.0048^\circ/\text{s}$, $\text{om}_z \approx 0.0031^\circ/\text{s}$.

Based on the above results, it can be concluded that among the deterministic errors, bias appears to have the greatest impact on the error propagation into the output signals. Additionally, white noise showed the highest error magnitude, thus also requires more investigation. In the next part of the paper, the influence of bias and white noise errors on the global position provided by the navigation system of an UAV will be examined.

Impact of IMU Errors on Positioning Accuracy

Strap-down Inertial Navigation System Architecture

A strap-down inertial navigation system was implemented in MATLAB/Simulink in accordance with Figure 8 (Grigorie, 2005).

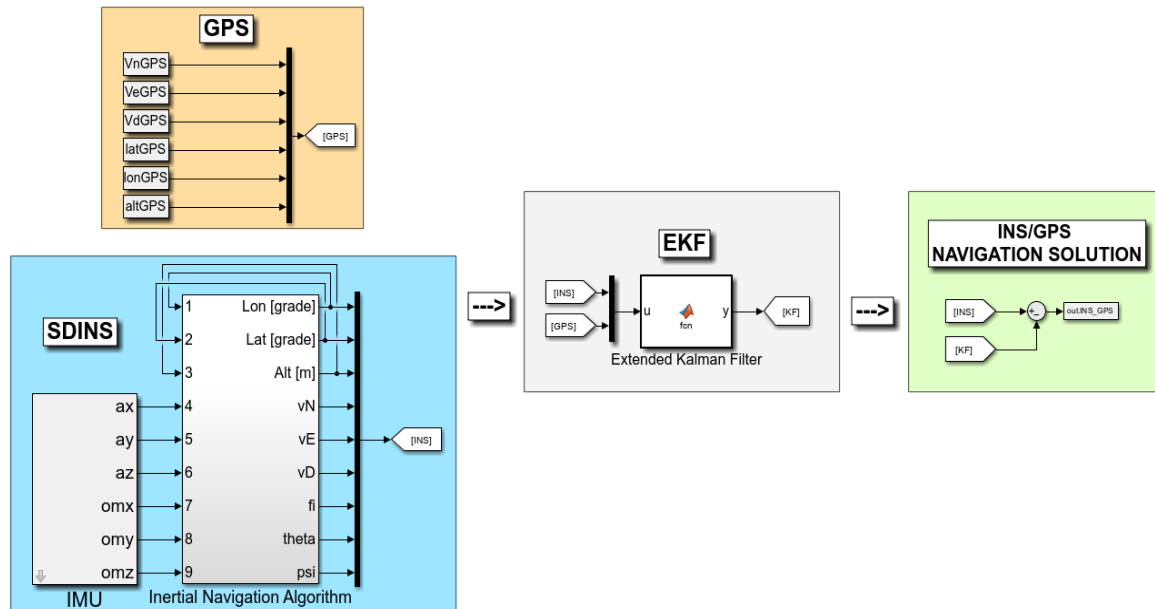


Figure 8. Simulink model of integrated INS/GPS system

The inputs of the navigator are the specific forces and angular velocities measured by IMU. The algorithm comprises two main parts: attitude determination and velocity/position estimation. In the first part, the Euler angles are computed (roll, pitch, yaw), while the second part provides the velocity and position in both North-East-Down (NED) (v_N , v_E , v_D) and Earth-Centered-Earth-Fixed (ECEF) frames, as well as geodetic coordinates (latitude, longitude and altitude) (Titterton, 2005).

In order to reproduce the navigation systems used in modern UAVs, a complementary system was added to the scheme, more exactly the GPS, which provides the speed in the NED frame and the global coordinates. The INS and GPS data are fused using an Extended Kalman Filter in order to correct estimated errors (Jwo, 2013).

Simulation of IMU Errors Effects on Integrated INS/GPS System

For the practical purpose of this study, the INS/GPS integrated architecture was simulated using real-flight data acquisitioned from an IMU mounted on an UAV. The sampling rate of both systems is equal to 100 Hz and the simulation time is set to 250 seconds (4 minutes and 10 seconds). The algorithm was first run with raw signals, and subsequently, errors were amplified in order to observe their impact on the navigation solution.

Firstly, a false bias value was introduced to IMU signals, as follows: 0.05 m/s^2 for accelerometers and $0.001^\circ/\text{s}$ for gyroscopes. This proved to have a direct influence on all three geodetic coordinates, but especially on the altitude, which dramatically decreased, simulating an accelerated descent scenario. Figure 9 shows the before and after estimated error given by the EKF.

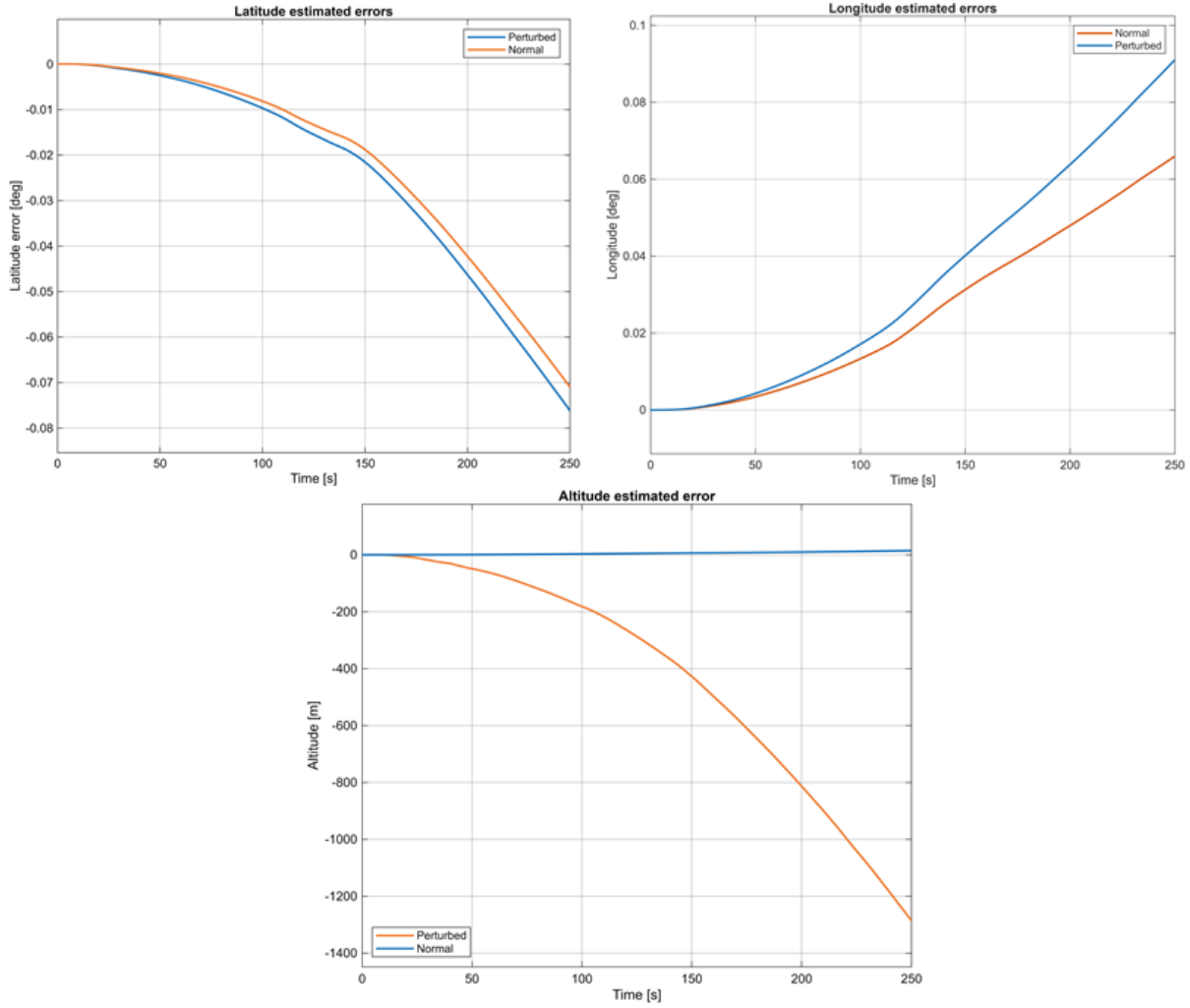


Figure 9. Estimated error results for normal and perturbed inputs (1)

For the latitudinal component, the statistical parameters obtained for the normal inputs were: $m=-0.021$, $\sigma=0.021$ and $RMS=0.0296$. After the introduction of artificial bias, the parameters became: $mean=-0.023$, $\sigma=0.023$ and $RMS=0.0324$. In this context, mean and RMS are particularly relevant, as they provide the signal's offset and dispersion around its mean. The perturbation of the input signals produced an increase of approximately 9.5% for each parameter over just four minutes of simulation. Although the EKF effectively manages the bias introduction, larger deviations may accumulate over longer time intervals.

The longitude estimated errors produced the following statistical parameters: $m=0.0254$, $\sigma=0.020$ and $RMS=0.0329$ in the initial case, and $m=0.0336$, $\sigma=0.029$ and $RMS=0.044$ in the second case. The raise was more notable in this case, being equal to approximately 33% for the mean and RMS, and 45% for the standard deviation. The longitude drift is highly influenced by the flight direction of the UAV and more pronounced in this case, due to the accumulation of gyro biases in the north and down directions (Cai, 2016).

Lastly, for the altitude component, the initial simulation provided the following values: $m=5.597$, $\sigma=4.453$ and $RMS=7.153$, with a maximum estimated altitude error of 15.195m. In the second simulation, the results were: $m=-414.169$, $\sigma=384.793$ and $RMS=565.328$, with a minimum value of -1285.84, thus simulating a sudden drop the UAV according to the INS data. The larger altitude error is given by the inherent sensitivity of the altitude component to biases, specifically the errors induced in the z-axis specific force, which accumulate by consecutive integration. (Li, 2025) The artificial 0.05 m/s^2 acceleration bias introduced to the accelerometers generates a theoretical altitude drift of approximately 1440m for the current flight time. This is consistent with the 1285.84 m value obtained in the simulation.

In the stochastic errors part, white noise was added to the input signals, starting from the following general values for the Noise Density: $0.17 \text{ mg}/\sqrt{\text{Hz}}$ for the accelerometers and $0.03^\circ/\text{sec}/\sqrt{\text{Hz}}$ for the gyroscopes.

The Noise Power was calculated in accordance with these values. The estimated errors before and after the perturbation of the signals are depicted in Figure 10.

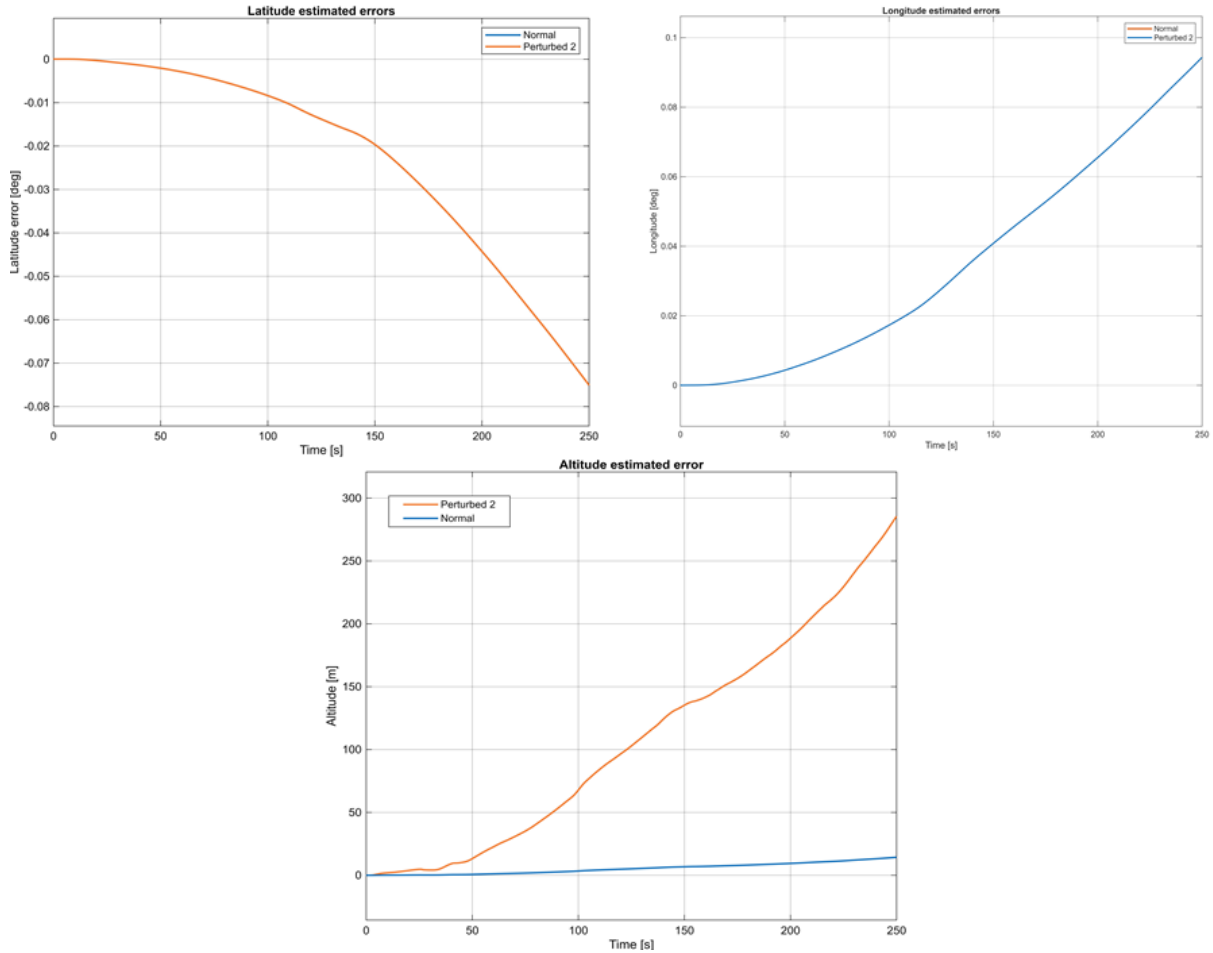


Figure 10. Estimated error results for normal and perturbed inputs (2)

In the second part of the experimental test, the introduction of a white-noise component into the input measurements caused minor deviations in longitude and latitude of 10^{-3} order. Nonetheless, the altitude component was clearly affected. The statistical parameters obtained were: $m=107.3620$, $\sigma=84.122$ and $RMS=136.392$, with a maximum error of 285.490 m, simulating a false altitude climb of the UAV. Once again, the altitude is influenced by the time integration of z-axis noise. Based on the magnitude of the white-noise introduced to the accelerometers, a theoretical altitude error of approximately 200 m was expected, which aligns consistently with the RMS and maximum values observed in this simulation.

Results and Future Prospects

In the first experimental part of this paper, both deterministic and stochastic errors of an IMU were studied under static conditions in a MATLAB/Simulink model. Among the deterministic errors, bias and scale factor error were found to have the greatest impact. In the case of stochastic errors, white noise and bias instability were identified as the most dominant sources. Consequently, bias and white noise were selected for further analysis in the second phase of the research.

The second experimental test focused on analyzing the impact of IMU errors on the navigation solution of an integrated navigation system similar to those used on modern UAVs. To this end, bias and white noise were artificially introduced into the IMU measurements. The study of bias effects showed that latitude and longitude experienced minor changes on the order of 10^{-2} , which may accumulate over longer time periods, with only longitude showing larger deviations. Altitude was, however, the most influenced by bias, with errors of up to 1300 m. When the white noise was introduced, latitude and longitude did not change significantly, with errors on the order of 10^{-3} , while the altitude error estimate reached almost 285 m.

Future prospects based on the current results include laboratory testing of industrial and tactical IMU sensors, as well as investigating the influence of external factors on the error propagation. Moreover, another field worth of further research refers to a broader range of evaluated errors, assessing the impact of the remaining deterministic and stochastic errors on positioning accuracy, and studying the combined effects of these errors.

Conclusion

This study was conducted under the premise that errors specific to miniaturized IMUs significantly disturb inertial navigation system outputs and the total accuracy of the navigation system. The problem was examined from two perspectives. In the first, low-level analysis was performed, deterministic and stochastic errors were closely evaluated to quantify the impact of each. Secondly, the problem was investigated from high-level perspective, the focus was placed on a navigation system resembling those included into modern UAVs. The influence of the most significant IMU errors was evaluated by artificially amplifying their magnitude and comparing the resulting geodetic parameters with the true values. The results demonstrate the negative impact that inherent IMU errors can have on the positioning accuracy of the monitored vehicle over short intervals of time. For longer flight durations and more complex scenarios, these effects would definitely be more pronounced and result in higher error levels.

In the light of the aforementioned aspects, the propagation of IMU errors throughout the inertial navigation algorithm, and their subsequent fusion with other navigation systems, can substantially impact UAV trajectory and autopilot performance, particularly over extended line-of-sight distances or in signal spoofing or blockage conditions, thereby jeopardizing the overall mission success.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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Author(s) Information

Antofie Bianca-Gabriela

Polytechnic University of Bucharest
Doctoral School of the Faculty of Aerospace Engineering
Splaiul Independentei no. 313, sector 6, Bucharest, Romania
ORCID iD: <https://orcid.org/0009-0002-8925-6362>
*Contact e-mail: bianca.antofie1512@stud.aero.upb.ro

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Scheduling Analysis in Digitizing Factories: An Application

Orhan Engin

Konya Technical University

Kadir Buyukozkan

Karadeniz Technical University

Ramazan Basar

Aksaray University

Abstract: The manufacturing companies should be dynamic and flexible for the customers' demands nowadays. Thus, scheduling plays an important role in these dynamics and flexibility. The manufacturing companies should make digitizing the operations and processors for online scheduling. In this research, the fourth industrial revolution is explained, a literature search is done for scheduling in the smart manufacturing environment, and the tools that are used during the digitized factories are defined. A simulation-based model is proposed for the smart factory in Industry 4.0 environment. Then an application is done in an office furniture manufacturing company in the smart factory environment. The physical model is transformed to virtual model by the proposed simulation approach at the production line where the office chair for executive and operational produced. With the three dispatching rules such as first in first out, earliest due date, and scatter search approach, a scheduling optimization is done in the office furniture manufacturing company. The efficient solution method is proposed for furniture manufacturing companies in the digitizing factories.

Keywords: Online scheduling, Digitizing factories, Scatter search method, Furniture manufacturing

Introduction

Industrial revolutions have been developed to increase productivity of the manufacturing environment. There have been four industrial revolutions to date. Industry 1.0 began in the eighteenth century and lasted for nearly a century. The steam-powered machines were used for production instead of human and animal-powered machinery and higher productivity was utilized. Then, Industry 2.0 started around the second half of the nineteenth century. In Industry 2.0, introduction to mass production was done. In Industry 2.0, the production lines were developed by Henry Ford and used in production intensively. The electricity-powered machines were used instead of steam-powered machines at production and productivity was increased. After that, in the second quarter of the twentieth century, Industry 3.0 revolution started with the invention of the first computer, the Z3. In Industry 3.0, analogue and digital technologies were used during the production line and higher productivity was obtained.

In recent six decades, the manufacturing systems have been transformed from mass products to customized products, namely large batch to low batch and mixed production due to customers' demands. The demands for customized products are forcing the companies' dynamic and flexible manufacturing environment. For dynamic and flexible manufacturing, companies should adopt new technological methods and solutions. One of them is Industry 4.0. Nowadays, the Industry 4.0 term is very popular in academia and industrial environments. Technological development led to the emergence of Industry 4.0. The Industry 4.0 revolution was proposed by the German government in the first quarter of the twenty-first century. The aims of the Industry 4.0 revolution

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for the German manufacturing industry are increasing the global competition on product quality and decreasing production costs. Industry 4.0 has provided flexibility, high product or service quality, short lead times, just in time manufacturing, and as a result maximum customer satisfaction.

Industry 4.0 is called by the different terms in many countries such as “Industry 4.0” or “Smart Service World” in Germany, “industrial internet” or “smart manufacturing” in the USA, “smart factory” in South Korea, “Smart Industry” in the Netherlands, “Internet of Things and Industry 4.0” in Italy, “Made Different” or “Marshall 4.0” in Belgium, “Alliance Industry of the Future” in France and “Made in China 2025” in China (Yang et al., 2019; Alemão et al., 2021). In Industry 4.0, the data is collected and store then analyzed. With analyzed data, the companies better understand inputs of the manufacturing system such as equipment, materials, etc. and output such as products or services. With Industry 4.0, the introduction to the cyber-physical system based on smart machines, sensors, big data, robots, Internet of Things, simulation, vertical and horizontal system integration, cyber security, cloud computing, augmented reality, etc. are provided (Malik & Kim 2020; Kaya et al., 2020).

Also, connectivity between the physical world and the virtual world is done. Industry 4.0 provides horizontal and vertical integration. It connects the value chain along with the product or service lifecycle. Horizontal integration connects the process from suppliers to manufacturers. Vertical integration combines hierarchical levels in the production or service system (Alemão et al., 2021).

In digital factories, many of the manufacturing resources are converted into intelligent objects. The manufacturing, in the digital factories, is called smart/intelligent manufacture. Also, the factories are called smart factories or dark factories. The digitalization of the manufacturing process started after the 1970s (Malik & Kim 2020). The rapid increase in the sensor and automation technology has occurred in the information technology for the integration of the manufacturing objects. The digital revolution has created smart factories with Industry 4.0.

In this chapter, a detailed literature review on smart manufacturing for scheduling is made for the first time. Also, the digitizing tools of smart manufacturing are explained in detail. In the transition to smart manufacturing, an application was made for the first time in a furniture manufacturing company. The rest of the chapter is organized as follows. In Section 2, the literature has been searched about smart/intelligent manufacturing in the concept of the Industry 4.0 perspective for the scheduling approach. Tools digitizing for smart factories is explained in Section 3. Application for a furniture manufacturing company is given in Section 4. With the conclusion and future research in Section 5, the chapter is concluded.

Literature Analysis

Companies should improve their productivity, product, and service quality. They also need to lower their production costs to compete in the market. For these aims, the companies can adopt several improvement models from academia. One of them is Industry 4.0, which has developed in the last decade. Industry 4.0 has been extensively researched in academia in recent years. In Industry 4.0, to increase the efficiency of the production system, the technologies and agents are integrated. The implementation of Industry 4.0 in the manufacturing environment is defined as smart manufacturing (Ahuett-Garza & Kurfess 2018). A detailed literature analysis has been done about smart/intelligent manufacturing in the concept of the Industry 4.0 perspective for the scheduling approach. The studies are given below.

Ivanov et al. (2016) considered an algorithm that simultaneous consideration of both machine structure selection and job assignments in smart factories in Industry 4.0. They studied the multi-objective, multi-stage flexible flow-shop scheduling problem in a dynamic scheduling environment. Ortiz et al. (2018) considered flexible job shop scheduling problems in the smart factory environment. At first, they analyzed the problem, then, the problem is mathematically formulated, and finally, they proposed a model. To show the applicability of the model, they conducted an example in a textile company. Zhang et al. (2019) investigated transferring traditional scheduling into smart distributed scheduling. They reviewed literature about job shop scheduling and determined the traditional scheduling methods and techniques which can be combined and reused in smart distributed scheduling, then they defined the new techniques for smart distributed scheduling.

Finally, they developed a scheduling model for solving the job shop scheduling problem under Industry 4.0. Lin et al. (2019) investigated the job shop scheduling problem of based on edge computing framework in a smart manufacturing factory. To solve the job shop scheduling problem, they used the Q network (which combines deep learning and reinforcement learning) with the edge computing framework. To determine the performance

of the proposed method, they made a simulation analysis. Malik and Kim (2020) proposed a task management mechanism based on resource-aware scheduling schemes. Their proposed mechanism uses two scheduling approaches. These are agent cooperation mechanisms and fair emergency first scheduling scheme. The agent cooperation mechanism goal is maximization per machine. Also, the goals of the fair emergency first scheduling scheme are minimizing the tasks starvation rate and maximizing machine utilization.

Moon and Jeong (2021) considered a deep Q-network for solving the job shop scheduling problem in a smart factory. They developed several cooperatively under the supervision of a cloud center for scheduling job processing. Zhou et al. (2021) proposed a reinforcement learning methodology for production scheduling in a smart factory. Their methodology is a composite reward function for data-driven scheduling of jobs under uncertainty in the smart factory environment. Their proposed model is first learned, second adapt, and then make scheduling decisions.

In a smart manufacturing environment, they tested their model with an experiment. In the other study, Zhou et al. (2021) proposed an artificial intelligence scheduler with novel neural networks to schedule dynamic operations. They designed reward functions to improve the performance of the proposed scheduler. They tested their proposed model in a smart factory through real-world case studies. Liaqait et al. (2021) considered the distributed job shop scheduling techniques in the industry 4.0 environments.

At first, they searched the studies about job-shop scheduling problems. Second, they classified the job shop scheduling problem. Third, they determined the solution algorithms for job shop scheduling, and finally, they integrated the job shop scheduling to industry 4.0 concepts. Ortíz-Barrios et al. (2021) proposed a multi-criteria approach for smart flexible job-shop systems. Their approach included the integration of the fuzzy AHP and TOPSIS. They used the fuzzy AHP to calculate the criteria weights under uncertainty. Also, they used TOPSIS for determining the rank of eligible operations. They employed their approach in the smart apparel industry. Alemão et al., (2021) searched the smart manufacturing scheduling approaches from the literature. They wanted to determine the constraints and targets of the manufacturing scheduling solutions in the literature studies. Also, they searched how the scheduling systems are designed and developed in the smart manufacturing environment.

Leng et al. (2022) investigated the dynamic scheduling problem within a "blockchain-networked" open manufacturing ecosystem. They proposed a decentralized iterative game theory approach to optimize resource sharing between smart factories. This study contributes to the Industry 4.0 vision of networked production by ensuring secure and transparent task allocation in distributed environments. Mourtzis et al. (2023) developed a "Digital Twin" (DT) based framework for real-time scheduling in smart manufacturing. Their approach utilizes real-time data from the physical production line via IoT sensors to dynamically update schedules. They specifically focused on increasing system resilience against unexpected machine breakdowns and sudden order changes, bridging the gap between virtual simulation and physical execution.

Zheng et al. (2024) addressed the assembly line scheduling problem under the emerging "human-robot collaboration" paradigm, reflecting the transition from Industry 4.0 to Industry 5.0. They utilized a multi-objective evolutionary algorithm to simultaneously optimize production efficiency (makespan) and worker ergonomics. The model was validated through an application in a smart electronics assembly factory. Sun et al. (2025) proposed a hybrid scheduling architecture for large-scale smart factories that combine Deep Reinforcement Learning (DRL) with Graph Neural Networks (GNN). By representing complex job workflows as graph structures, their model analyzes the relationships between tasks more effectively than traditional methods. Their results demonstrated superior performance and faster decision-making under high-frequency dynamic job arrivals.

Digitalization of the Factories

The main elements of the Industry 4.0 are the Internet of Things, Big Data, Cyber-Physical Systems, Additive Manufacturing, Robotics, and Machine Learning, Artificial Intelligence, and Digital Twin but not restricted only to these elements. For the digitalization of the factories, these elements should be integrated. The integration of these elements in the manufacturing environment is defined as a smart factory. In smart factories, the manufacturing resources such as materials and machines are integrated based on IoT and coordinated by scheduling algorithms (Zhou et al., 2021). The flow chart for the Industry 4.0 is given in Figure 1. The elements of the smart factory are explained as follows.

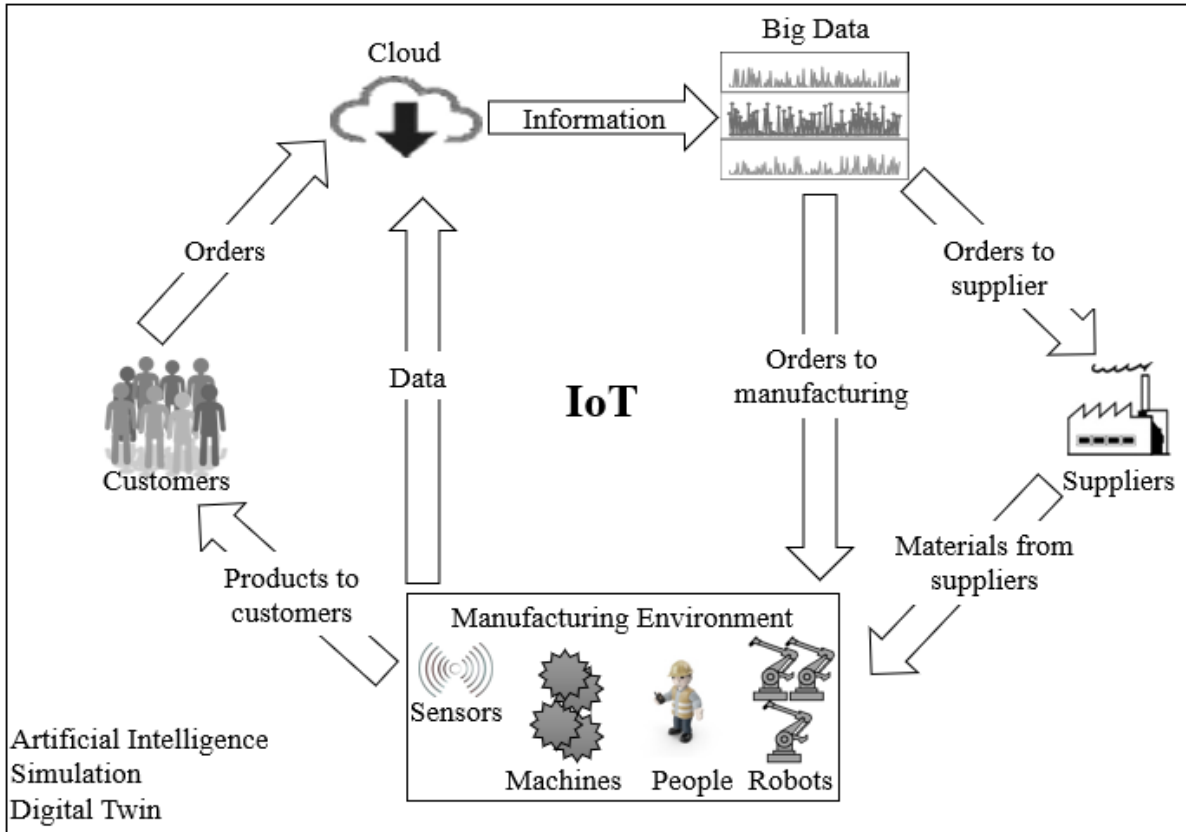


Figure 1. The flow chart of Industry 4.0 (Ahuett-Garza & Kurfess, 2018)

Internet of Things

The internet's access and connectivity are present in every stage of human life today. The internet evolution is given in Table 1. Here, the internet refers to internet-networking supported by wired and wireless technologies such as Ethernet, Wi-Fi, Bluetooth, ZigBee, radio frequency identification (RFID), or barcodes. Things refer to the physical and/or virtual objects which collect and/or exchange data. Vehicles, sensors, machines, robots, and humans, etc. are an example of things (Yang et al., 2019).

Table 1. The internet evolution (Yang et al. 2019)

Internet evolution area	Began and evolution dates
Telecommunication (Telephone, mobile phone, smartphone)	1844-2007-continue
Internet of Contents (emails, web browser, HTMLs)	1960-1989-continue
Internet of Services (E-commerce)	1995-1998-continue
Internet of People (LinkedIn, Facebook, Twitter, Google)	2003-2012-continue
Internet of Things (Sensors, actuators, etc.)	1999-continue

It can be seen in Figure 1; the Internet of Things (IoT) is one of the main elements of the Industry 4.0 revolution and smart factories. IoT is defined as the integration of objects. In the IoT, "Things" include sensors, actuators, materials, robots, machines, products, material handling equipment, and human operators, etc. (Yang et al. 2019). This integration is provided by embedded devices such as sensors, radio frequency identification, etc. which are connected by networks. IoT integrates things inside a manufacturing environment and with the outside environment. The control hierarchies of the IoT are Manufacturing Execution Systems and Enterprise Resource Planning. IoT has smart tags, smart sensing technologies, location tracking, etc. IoT connects smart machines to the network. The virtual twin of the physical world is created through the integration of IoT and

cyber-physical systems. With IoT technology, each physical object in the manufacturing process has its virtual representation (Malik & Kim, 2020). Digital factories use the combination of Internet of Things technologies.

Cyber-Physical Systems (CPS)

The physical world relates to the virtual world through cyber-physical systems. The virtual objects are replicates of the physical objects in a virtual network. The integration of the IoT and cyber-physical systems creates a virtual twin (Malik & Kim, 2020). This integration is shown in Figure 2.

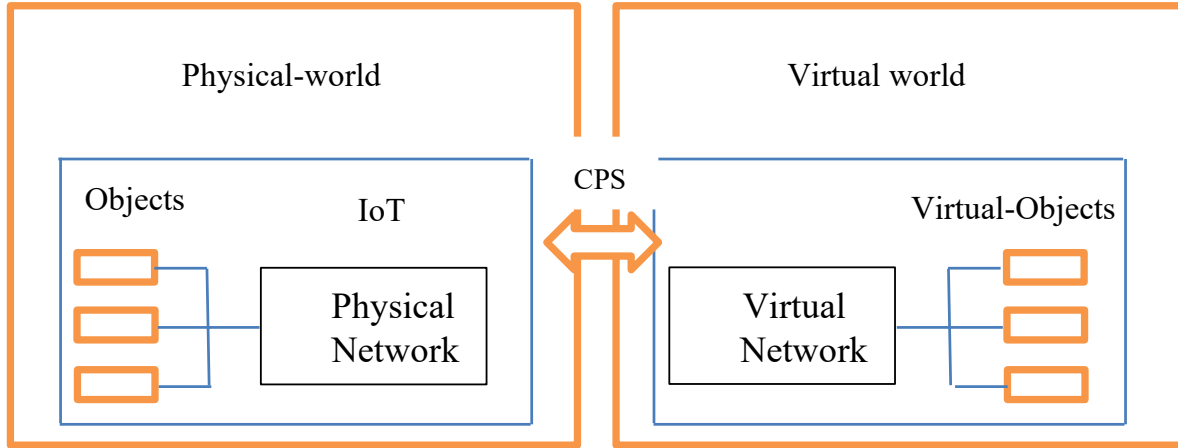


Figure 2. Integration of the IoT and CPS (Malik & Kim, 2020)

It can be seen in Figure 2; CPS connects the physical world to the virtual world. In the smart factory, cyber-physical system operates the operations.

Big Data

In the smart factory, with the sensors, radio frequency identification, etc. Huge volumes of data are collected from machines and other physical and virtual objects in the manufacturing environment. This data is known as big data. The big data updates dynamically the resources used for production and unexpected disturbances such as machine failures. To increase productivity and customers' satisfaction by minimizing products and service costs this big data should be collected and analyzed. During the analysis of this big data, artificial intelligence and machine learning approaches can be used for interpreting. The useful information can be extracted from the big data by the artificial intelligence and machine learning approaches and is used for smart manufacturing objectives such as maximizing the product quantity, customer satisfaction, and machine utilization and minimizing the production cost, and production time.

Additive Manufacturing

In Additive manufacturing, materials are joined by layer upon layer methodology to make objects from 3D model data (Bikas et al., 2016). By additive manufacturing, we can produce very intricate and complex geometries parts with near-zero material waste, including plastics and metals (Bikas et al., 2016).

Robotics

The use of robots in the manufacturing process is increasing flexibility, productivity, and quality. It also reduces manufacturing product costs and delay times for orders. It contributes to just-in-time production.

Machine Learning

The big data, which is collected in the manufacturing environment by sensors, radio frequency identification, etc., is analyzed by using a machine learning approach to extract the predictive maintenance, fault detection, and product's quality detection knowledge.

Artificial Intelligence

The artificial intelligence term first occurred in 1956 for machine simulating problems. Artificial intelligence is a field of computer science that replicates human intelligence (Zhang et al., 2019). Artificial intelligence learns from data and accumulated experience, and it proposes a dynamic solution for production problems.

Digital Twin

Also, digital twin can be used to build smart factories. The digital twin is a replica of a physical entity in the manufacturing environment. Before the actual production systems are built, with the construction of the digital twin systems, the problems which occur during the customized smart manufacturing can be identified before. These problems can be solved before optimal decisions can be made. Also, the digital twin can be used during the manufacturing process for optimization of operation, maintenance, and fault diagnosis. The digital twin increases the importance of modeling and simulation (Kim et al., 2019).

The digitalization of the factories has emerged the smart/intelligent factories. The performance of smart factories is dependent on the architectural design and scheduling optimization approach. In digital factories, real-time data is shared and devices, machines, and other objects are smart and interact with each other.

Application

Nowadays, to meet the market demands, companies should be more dynamic and flexible. Also, they can be adjusted and continue to improve their manufacturing process to the change in the global market. For this reason, scheduling is very important in the dynamic and flexible manufacturing process. The effectiveness of the manufacturing process, the satisfaction of the customers, the costs of the products and services, etc. are dependent on the scheduling methods' performance. There are a few methods for solving the scheduling problems from the literature. These are knowledge-based, simulation methods, exact methods, heuristic, and metaheuristic methods. In smart factories, during the scheduling process, usually the modeling and simulation methods are used to continuous improvement the production system. For production simulation, there are many commercial tools and environments such as layout design, scheduling, and fault diagnosis (Kim et al., 2019).

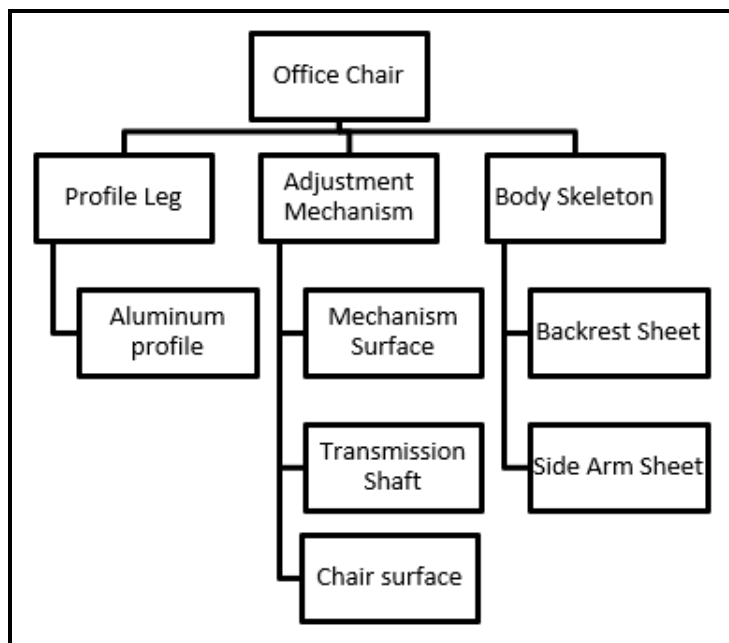


Figure 3. The product tree diagram of the office chair for executive and operational

In this study as a scheduling optimization approach, a simulation-based method is used for smart manufacturing in the Industry 4.0 environment. In the research, we focus on dynamic scheduling in a smart factory environment. Dynamic scheduling is a combinatorial optimization problem. We proposed a simulation model for dynamic scheduling problems at the office furniture manufacturing company in the smart factory environment. With the simulation model, we transformed the physical model to virtual model. The company is founded at Konya in Turkey. The company produces office furniture. The application is made on the production line where the office chair for executive and operational produced. The product tree diagram of the office chair for executive and operational is given in Figure 3.

Table 2. The tasks and definition architecture of the proposed model

Tasks	Type	Function	Definition of architecture
1-2	Information Technology	Assign numbers to the orders	The taken on-line orders by product reference number are transferred to production by giving an order number. The due date of the orders is determined.
3	Information Technology	Determine the material requirement	An intelligent decision system creates a work order for each part to be produced by calculating the sub-part needs according to the product types in each order.
4	Information Technology	Hold the orders until delivery	The architecture model keeps the order information until the order is produced and automatically sends information to the customer when the ordered products are ready, with the approval of an authorized person
5 – 16	Information Technology	Generate barcode number	A barcode number is generated for each sub-product of each order. With this barcode number, all information about the order can be tracked.
17-28	Barcode / Smart Jobs	Makes products smart	Barcode numbers produced in the architecture model are added to each piece. In this way, the product turns into a smart product (smart Jobs) that carries its own order information. These barcode numbers can also display machine route information, processing times information, etc.
29–36	Smart Machines (press, saw, laser cutting, weld)	Intelligently produces	Intelligent machines in the manufacturing processes can communicate with smart products and determine the set-up times that will occur between input and output parts.
37–46	Smart robot arms with smart inference systems	Load the parts to the systems based on rules	Through the sensors on the robot arms, a connection is made between the smart semi-finished products and the workstations. Semi-products are directed to the empty workstation for processing. When the workstation is full, the smart semi-finished products are kept in the buffer. When any workstation is emptied, according to the prioritization rule, semi-finished products are forwarded to that workstation for processing.
47–56	Sensor technology	Recognize smart jobs	The sensors detect the semi-finished products passing through the relevant point by reading the barcodes on the smart semi-finished products. Then, the setup times of the semi-finished products in the machines are determined.
57-69	Automated driving technology	Divert the products automatically	Intelligent conveyor systems, communicate with intelligent semi-finished products to be assembled and automatically direct these semi-finished products to the area where other sub-parts are located. Then, the sub-parts to be assembled are collected in a box. When all sub-parts are completed, these sub-parts are transported to the assembly station for assembly.
70, 71	Sensor technology	Recognize smart jobs	The sensor determines the completed orders by communicating with the smart products that have been assembled.
72-76	Information Technology	Arrange the delivery	Completed orders are sent to the loading department and shipment information is sent to customers via RFID.

As can be seen in Figure 3, the executive and operational office chair consists of a series of sub-assemblies, and each subassembly consists of a series of operations, and each operation is processed in order of priority on the suitable machines. The considered scheduling system, which executive and operational office chair production line in the smart factory environment is a hybrid flow shop scheduling with multi-layer assembly problem.

For the sensing tasks, the sensors are installed in the line of production. Machines and robots are controlled and directed with these sensors. The real-time data is collected from the machines and robots by these sensors such as jobs arriving at the machine and robot, operation time, machine and robot fault, machine and load balancing, machine and robot utilization, etc. This data is used for machine learning mechanisms. In other words, this data is used for building a knowledge-based mechanism by simulation model on application ex-ample. This knowledge has increased the efficiency of the proposed simulation model. The company has an e-catalog on the web page. The customers select the office chair for executive and operational from e-catalog and order by the product reference number to the company. The objective is to minimize the number of delayed customers' orders and makespan. Customer orders are processed as one piece on the production line. In other words, we adopted one-piece flow in the proposed model. The proposed simulation-based model architecture is explained as follows. First, the task and definition architecture is given in Table 2. The production line is given in Figure 4.

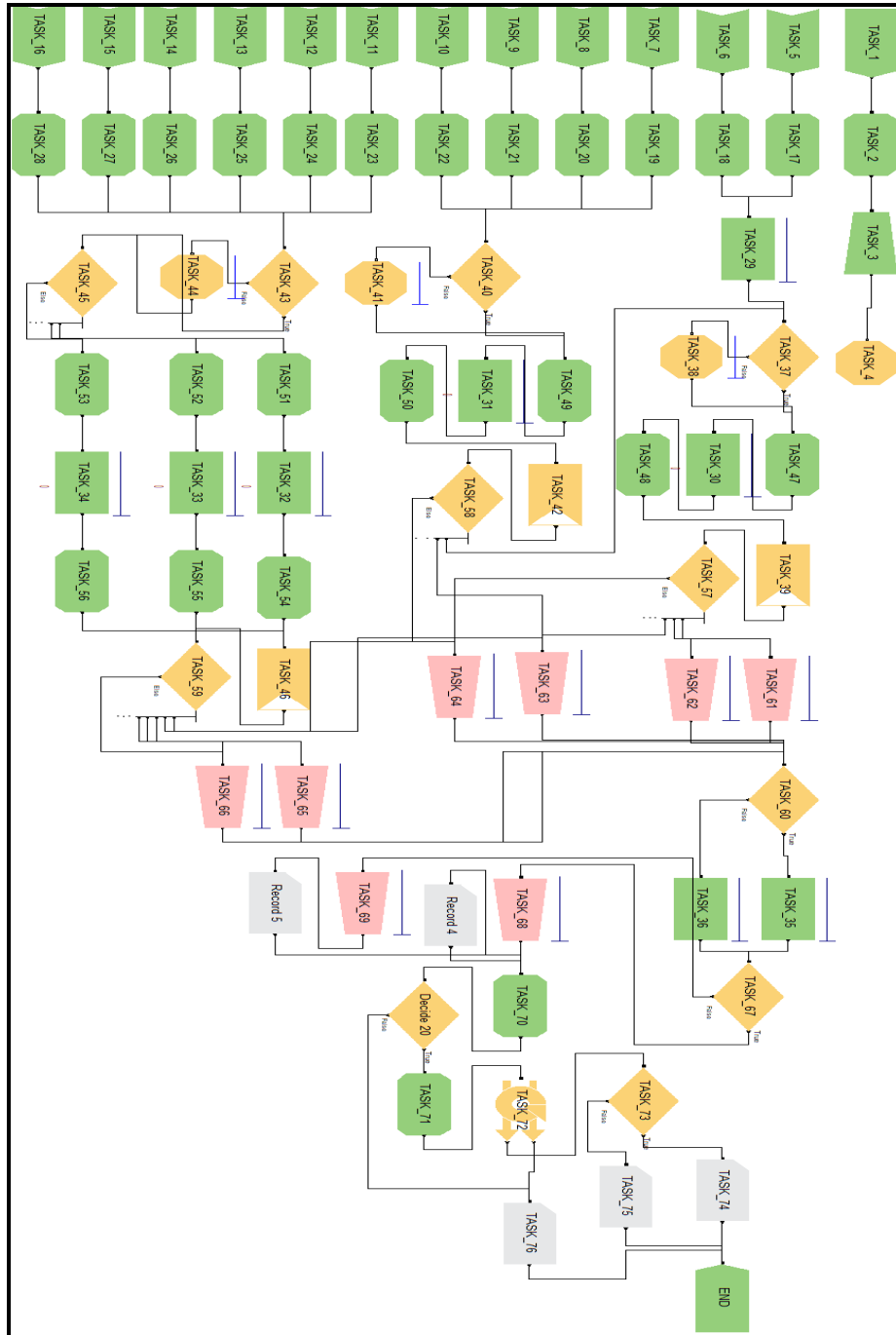


Figure 4. Production line of office chair for executive and operational

The simulation model is built using Rockwell Arena, ver-sion;16.10.00001. The proposed model is run on a Core i5-4210U 3.6 GHz CPU with the Windows 10 operating system (Shiue et al., 2018). The proposed simulation model uses three dispatching rules for optimization. These are the first in first out (FIFO), earliest due date (EDD), and scatter search approaches. The proposed scatter search approach is explained as follows.

Scatter Search Method

Scatter search is an evolutionary approach that developed in the 1970s (Engin et al., 2009; Engin et al. 2013). The proposed scatter search approach steps are given as follows (Külahlı et al., 2021; Başar et al., 2022; Oktay & Engin, 2006).

- Step 1: Create an initial population by random,
- Step 2: Generate a reference set from the population,
- Step 3: Select a subset from the reference set,
- Step 4: Apply a combination procedure to subset,
- Step 5: Apply an improvement method to the combinations,
- Step 6: Update the reference set,
- Step 7: Repeat until the reference set is met,
- Step 8: Repeat until the population size is met,
- Step 9: Repeat until the stopping criterion is met,

During the application of the simulation-based model for executive and operational office chair production line in the smart factory environment, three dispatching rules are used for optimization. The performance of these three dispatching rules is given in Table 3.

Table 3. Performance of various dispatching rules in the Industry 4.0 simulation model

Dispatching Rules	Number of delayed customer orders
First in First Out (FIFO)	2
Earliest Due Date (EDD)	1
Scatter Search	1

It can be seen in Table 3 that in the digital factories, during the scheduling process for optimization several dispatching rules should be used in the simulation model. In this research three dispatching rules are used to sequence the customer's order. The statistics of the simulation model used are given in Table 4.

Table 4. The statistics of the simulation model

Time Statistics	Values (minutes)	
	FIFO	EDD
Order Delivery Cycle	21.21	11.66
Total Completion Time (C_{max})	81.03	73.22
Number of delayed customer orders	2	1

Conclusion and Future Research

In recent years, due to customizing the products and services demands, the manufacturing companies have had to increase productivity and customers satisfaction by minimizing products and service costs. For these new situations, new production improvement methods have occurred. These are lean production, agile manufacturing, and in Industry 4.0 environment smart manufacturing. In this study, the Industry 4.0 revolution is investigated. The scheduling studies in smart manufacturing are searched from the literature. The tools for digitizing factories are analyzed. A case study is done in an office furniture manufacturing company.

The physical production line where office chairs for executive and operational produced is transformed into a virtual model by the proposed simulation approach. The Rockwell Arena package is used for modeling digital factories. For scheduling optimization, three dispatching rules are proposed.

In future research, the proposed scatter search approach can be hybrid with the other methods to improve the performance of scheduling optimization. Also, the proposed simulation model can be used in the other production line in the company for other office furniture products.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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Author(s) Information

Orhan Engin

Konya Technical University
Engineering and Natural Science Faculty
Industrial Engineering Department, Konya/Türkiye
ORCID iD: <https://orcid.org/0000-0002-7250-0317>
*Contact e-mail: oengin@ktun.edu.tr

Kadir Buyukozkan

Karadeniz Technical University
Industrial Engineering Department, Trabzon, Türkiye
ORCID iD: <https://orcid.org/0000-0001-6321-0302>

Ramazan Basar

Aksaray University
Industrial Engineering Department, Aksaray, Türkiye
ORCID iD: <https://orcid.org/0000-0001-5416-4914>

*Corresponding author(s) contact email

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High Mass Ratio Tuned Mass Dampers Obtained Through Building Superelevations for Seismic Retrofit

Rosario Montuori
University of Salerno

Elide Nastri
University of Salerno

Pasquale Roberto Marrazzo
University of Salerno

Abstract: Tuned Mass Dampers (TMDs) are widely adopted passive vibration control devices used to mitigate structural oscillations induced by wind and seismic actions. Conventional TMD systems typically involve relatively small auxiliary masses installed near the top of tall buildings. This paper investigates an alternative strategy for seismic retrofitting of existing structures based on large mass ratio TMDs obtained through building superelevations. In this approach, one or more additional storeys supported by seismic isolation devices behave as large tuned masses capable of reducing structural response during earthquake excitation. A comprehensive parametric numerical investigation is carried out in order to evaluate the influence of the mass ratio, structural period and damping characteristics on the effectiveness of the system. The results are summarized in a set of design charts that allow engineers to determine optimal tuning parameters. In particular, by using the obtained design abaci they can find a solution which minimizes both displacement and acceleration.

Keywords: Tuned mass damper, Retrofitting, Large mass ratio

Introduction

Tuned Mass Dampers (TMDs) represent one of the most widely used passive control systems for mitigating structural vibrations. The concept is based on the introduction of an auxiliary mass connected to the main structure through elastic and damping elements. When the system is properly tuned, the auxiliary mass oscillates out of phase with the primary structure, thereby dissipating a portion of the input energy (Alibabaei et al., 2023; Clarizia et al., 2024; De Angelis et al., 2012; Den Hartog, 1956; Giaralis et al., 2018; Gorini et al., 2019, 2022, 2024; Kaveh et al., 2020; Marrazzo et al., 2024; Salimi et al., 2021; Wang et al., 2020; Zucca et al., 2021). The effectiveness of this strategy has been widely demonstrated in tall buildings subjected to wind and seismic loads. A well-known example is the Taipei 101 skyscraper (Figure 1), which incorporates a 660-ton pendulum damper installed near the top of the building to control wind-induced vibrations.

Similar devices have been installed in several high-rise buildings around the world. In conventional applications, the auxiliary mass typically represents only a small percentage of the total structural mass, generally ranging between 1% and 5%. However, recent research has investigated the possibility of employing larger mass ratios in order to enhance vibration control efficiency.

One promising strategy for achieving high mass ratios consists of adding new storeys above existing buildings, supported by seismic isolation devices. In this configuration, the additional structural mass behaves dynamically as a tuned mass damper. This approach offers several advantages. First, it can significantly improve the seismic

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performance of existing structures designed according to outdated seismic standards. Second, the intervention can generate additional usable space, potentially offsetting retrofit costs. For these reasons, superelevation-based TMD systems represent an attractive solution for the seismic upgrading of existing buildings.

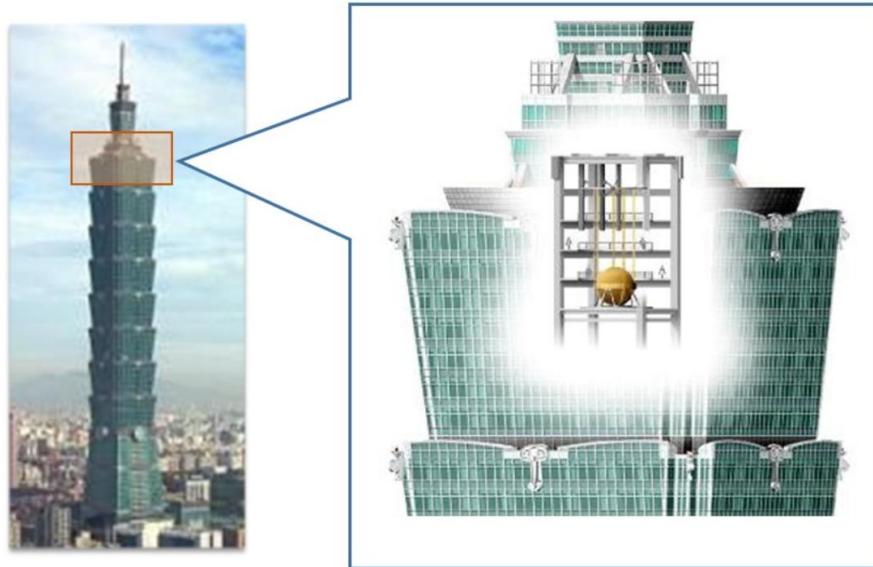


Figure 1. Tuned mass damper of 101 Tower– Taipei

The effective of this type of retrofitting has been already proved in two cases: The Berry Street project in San Francisco (Figure 2) where two isolated stories have been added to an existing three storey building, and the retrofitting by means of a superelevation of one floor made by steel structure by Marco Peroni in Faenza Italy (Figure 3).



Before the superelevation



After the superelevation

Figure 2. Berry Street Building, San Francisco



Before the superelevation

After the superelevation

Figure 3. Superelevation in Faenza by Marco Peroni

Methodology

The problem to be analyzed can be represented by the model in Figure 4

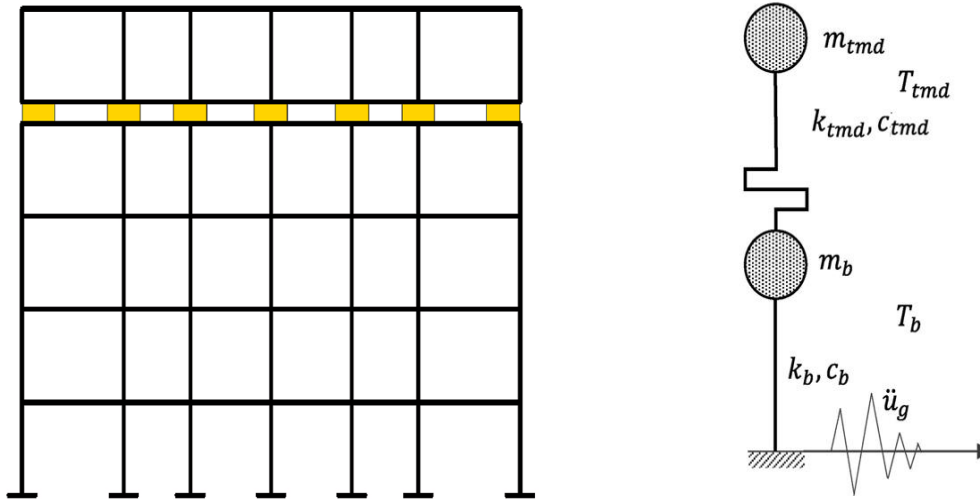


Figure 4. Modelling of the TMD

The dynamic behaviour of the mechanical model composed of two masses, namely the base mass m_b and the TMD mass m_{tmd} , characterized by natural frequencies $\omega_b = \sqrt{k_b/m_b}$ and $\omega_{tmd} = \sqrt{k_{tmd}/m_{tmd}}$ and damping ratios $\xi_b = \frac{c_b}{c_{b.crit}}$ and $\xi_{tmd} = \frac{c_{tmd}}{c_{tmd.crit}}$ has been investigated under several seismic ground motion records. The numerical simulations were carried out by varying the parameters associated with the system, namely the two natural frequencies, the relative mass ratio $\bar{m} = m_{tmd}/m_b$, and the damping ratio of the TMD ξ_{tmd} . The damping ratio of the main structure ξ_b was kept constant and equal to 0.05, which is commonly assumed for reinforced concrete (RC) structures. The purpose of the parametric study is to identify the combination of parameters that minimize the structural response of the building in terms of both absolute displacement and acceleration.

The parametric investigation was performed by varying the input parameters summarized in Table 1. In particular, the mass ratio $\bar{m}$, the TMD damping ratio ξ_{tmd} , the vibration period of the base structure T_b , and the vibration period of the TMD T_{tmd} were treated as variable quantities. A set of 100 artificial ground motion records was generated to approximately match (within $\pm 10\%$) the Eurocode 8 design spectrum for soil type A, considering an

intermediate peak ground acceleration (PGA) value of 0.15 g. Each record has a duration of 20 seconds and was generated using the well-known software SIMQKE.

Table 1. All the combinations are made for parametric analyses.

$\bar{m}$	0.10	0.20	0.30	0.40
ζ	0.15	0.20	0.25	0.3
T_b and T_{md}	0.00-4.00s step 0.04s			

The obtained results were statistically processed by evaluating the upper bound fractile (95%) of the structural response obtained from the time-history analyses, considering both displacement and acceleration as response parameters.

Results and Discussion

A very useful representation for design purposes is obtained by analysing the displacement response as a function of the TMD period for a given base structure period. In this case, the displacement response of the base SDOF coupled with the TMD exhibits a clear minimum value that corresponds to the optimal tuning condition of the system. By comparing this response with the displacement obtained for the uncontrolled SDOF system (i.e., without TMD), it is possible to evaluate the effectiveness of the vibration control device. In several cases the presence of the TMD leads to a significant reduction in displacement; however, for certain combinations of the TMD vibration period the displacement of the base structure may increase instead.

A similar analysis was performed considering the structural response in terms of spectral acceleration. The results confirm that the tuning relationship between the structural period and the TMD period strongly influences the dynamic response of the system. When the auxiliary mass is properly tuned, a clear reduction in acceleration demand is observed with respect to the uncontrolled SDOF system. Consequently, these results can be used as a practical design tool when the reduction of acceleration represents the main performance objective. The results of the study are further summarized in terms of normalized displacement and acceleration, obtained by dividing the response of the controlled system by the corresponding response of the uncontrolled SDOF system. The legend adopted for these representations is reported in Table 2.

It is important to clarify the range of base structure periods considered in the analyses. Although the complete parametric investigation explored a wide range of structural periods from 0 to 4.0 s, the analyses used to develop design-oriented charts focus on a narrower interval between 0.50 s and 1.50 s, with increments of 0.20 s. This choice is motivated by the observation that it is uncommon for existing buildings to exhibit fundamental vibration periods exceeding 1.5 s. Since the proposed abaci are intended for application to existing structures, the investigation was concentrated within this more realistic range of structural periods. The results indicate that the damping ratio of the TMD has a limited influence on both displacement and acceleration of the base structure until the optimal tuning condition is reached. After this point, however, a significant dispersion among the response curves can be observed.

Another important observation concerns the influence of the mass ratio on the optimal tuning condition. For relatively small mass ratios, the minimum displacement response is obtained when the vibration period of the TMD is approximately equal to that of the base structure. Conversely, for larger mass ratios the optimal condition shifts toward higher values of the TMD period, which may reach values close to 1 s when the mass ratio is equal to 0.40.

The normalized response diagrams derived from the parametric analyses can therefore be used as practical design tools for the dimensioning of non-conventional TMD systems applied to existing structures. In the design phase, the main characteristics of the building, namely the structural mass m_b and the fundamental period T_b , are typically known. For a given value of the mass ratio $\bar{m}$, the optimal design solution can be obtained using the abaci derived from the parametric analysis, which allows the corresponding value of T_{mb} to be determined.

Overall, the results show that properly tuned systems can significantly improve the structural response. In particular, reductions in maximum top displacement greater than 30% and decreases in peak acceleration exceeding 40% were observed. In some cases the increase in seismic performance could be dramatically high. As an example, when in the existing structure there is the development of a soft storey mechanism, which nowadays is avoided by adopting specific design procedure (Montuori et al. 2015, Montuori et al. 2017), the superelevation

allows to avoid the development of this brittle and low dissipative mechanism. Similarly, the problem of residual drift is avoided (Montuori et al 2021, Montuori et al. 2024) because the structure remains in elastic range.

Table 2. Legend of figure 4 to 8

		$T_{base} [s]$					
		0.5	0.7	0.9	1.1	1.3	1.5
TMD damping	0.15						
	0.2						
	0.25						
	0.3						

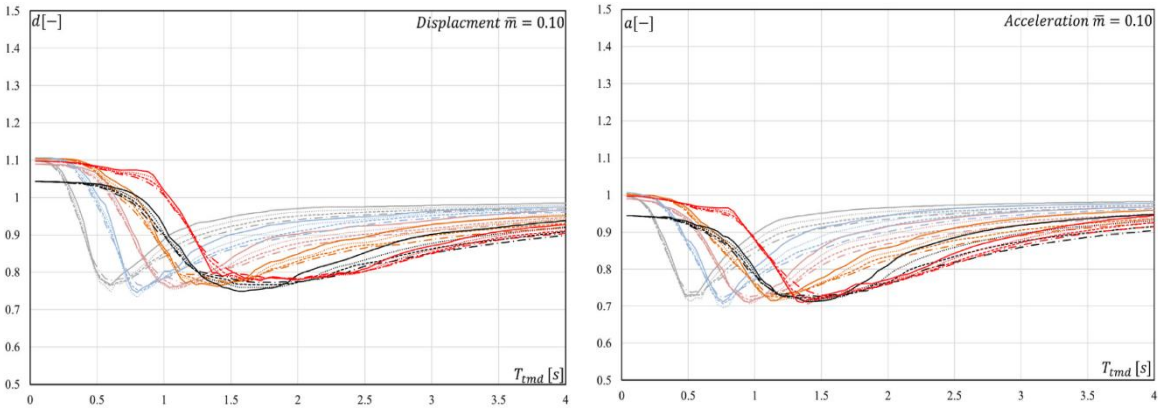


Figure 4. Dimensionless displacement (left) and dimensionless acceleration (right) with $\bar{m} = m_{tmb}/m_b = 0.10$

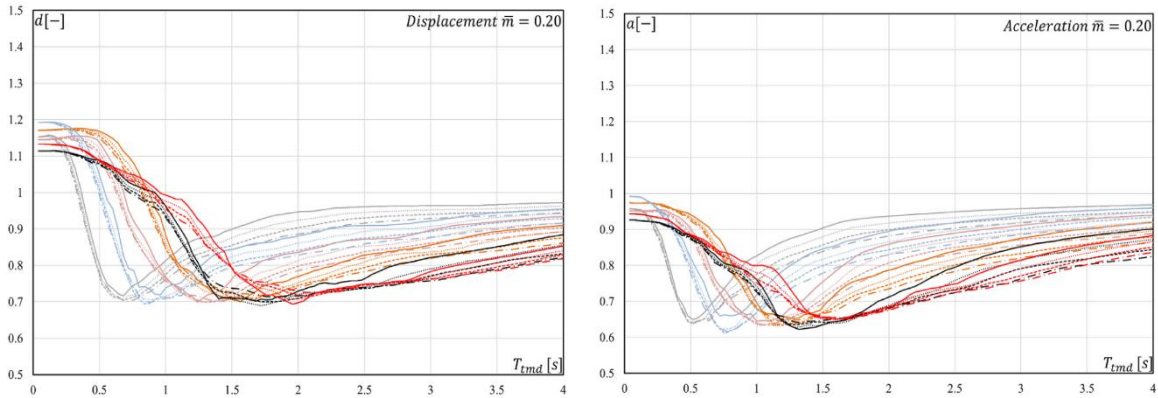


Figure 5. Dimensionless displacement (left) and dimensionless acceleration (right) with $\bar{m} = m_{tmb}/m_b = 0.20$

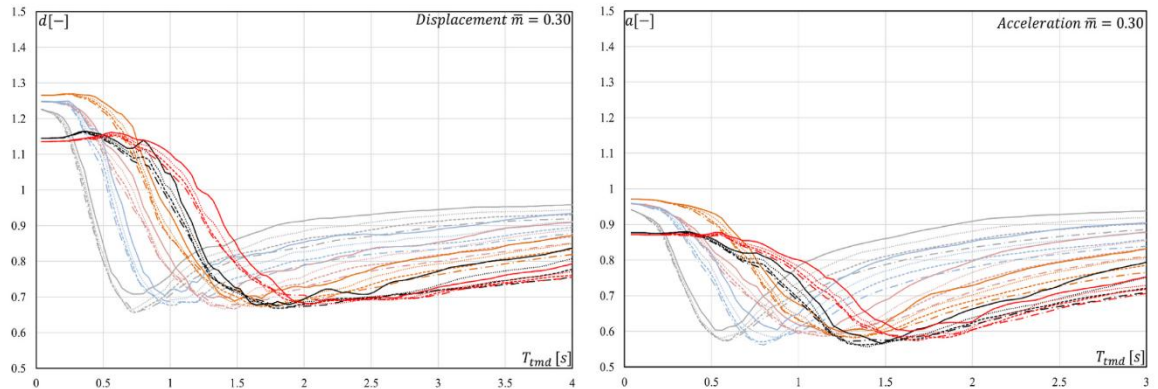


Figure 6. Dimensionless displacement (left) and dimensionless acceleration (right) with $\bar{m} = m_{tmb}/m_b = 0.30$

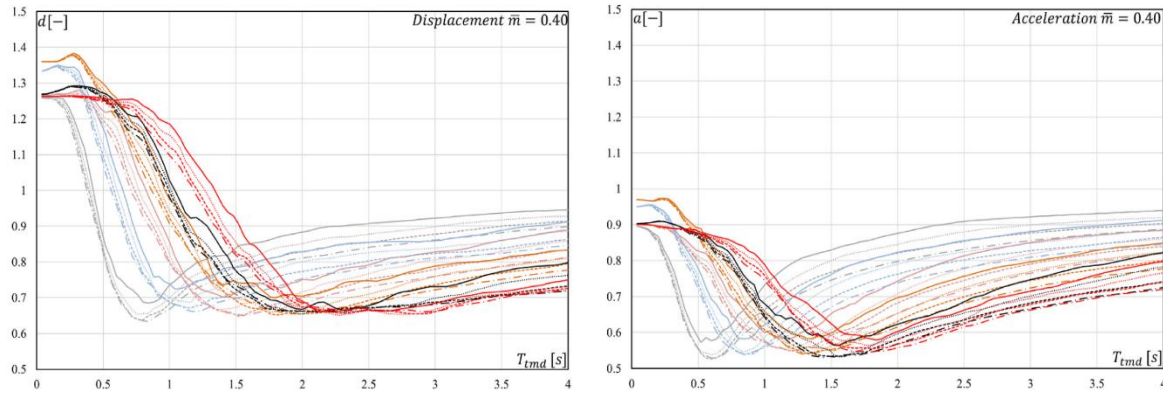


Figure 6. Dimensionless displacement (left) and dimensionless acceleration (right) with $\bar{m} = m_{tmb}/m_b = 0.4$

Conclusion

This study investigates the use of non-conventional Tuned Mass Dampers (TMDs) characterized by high mass ratios as a strategy for the seismic retrofitting of existing buildings, particularly those designed according to outdated seismic design criteria. The proposed concept is based on the addition of one or more new storeys above the existing structure, separated from it through the installation of seismic isolation devices.

An extensive parametric investigation was carried out using a simplified mechanical model with two degrees of freedom (1 + 1 DOFs). The analyses considered a wide set of seismic ground motions while varying the main governing parameters of the system, namely the mass ratio and the damping properties of the TMD. The results were summarized in the form of design-oriented charts (designer-friendly abaci) developed to optimize both displacement and acceleration responses of the base structure. These charts provide a practical tool for identifying the optimal configuration of the system during the design phase.

From a practical perspective, the proposed strategy is particularly attractive for existing buildings designed without seismic provisions. In many of these structures the safety factors with respect to vertical loads are often greater than unity, whereas the capacity to resist horizontal seismic actions is generally insufficient. This condition frequently makes it possible to introduce one or more additional storeys without exceeding the vertical load capacity of the existing structural system.

An additional important aspect concerns the economic feasibility of the intervention. The construction of new habitable volumes generated by the superelevation can represent a substantial economic benefit which, when feasible, may offset a significant portion of the retrofit costs and in some cases even cover the entire intervention, resulting in a net economic advantage.

Furthermore, when strengthening interventions on the existing structure are required, they are typically limited to the vertical structural elements rather than to the beams. In fact, following the introduction of the superelevation-based TMD system, seismic demands acting on the structure are reduced while vertical loads increase. As a consequence, the strengthening demand tends to shift from beams to columns. This aspect is particularly advantageous because interventions on columns are generally simpler and more cost-effective compared with strengthening of beam elements.

Overall, the results demonstrate that the adoption of non-conventional high-mass-ratio TMD systems represents a promising approach for improving the seismic performance of existing buildings. The proposed design abaci provide a practical framework for supporting retrofit interventions aimed at reducing both displacement and acceleration demands during earthquake excitation. The findings highlight the significant potential of high-mass-ratio TMDs for the seismic upgrading of buildings designed with outdated criteria, contributing to the development of more resilient built environments.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

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Author(s) Information

Rosario Montuori

University of Salerno

Via Giovanni Polo II, 84084, Fisciano, Italy

ORCID iD: <https://orcid.org/0000-0002-6323-5419>

Contact e-mail: r.montuori@unisa.it

Elide Nastri

University of Salerno

Via Giovanni Polo II, 84084, Fisciano, Italy

ORCID iD: <https://orcid.org/0000-0002-4880-9672>

Pasquale Roberto Marrazzo

University of Salerno

Via Giovanni Polo II, 84084, Fisciano, Italy

ORCID iD: <https://orcid.org/0000-0001-6673-0071>

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Next-Generation Multifunctional Composites: The Role of MXene Nanosheets in Enhancing Fiber-Reinforced Epoxy Polymers

Muhammed Huseyin Guzel
Konya Technical University

Abstract: Fiber-reinforced polymer composites are indispensable in high-performance engineering sectors. This study investigates the potential of MXenes as advanced reinforcing agents for carbon, glass, basalt, and Ultra High Molecular Weight Polyethylene (UHMWPE) epoxy composites. It presents a comparative analysis evaluating the effects of the primary MXene synthesis methods: Direct HF etching method and the Minimally Intensive Layer Delamination (MILD) method using LiF/HCl. Literature synthesis reveals that MXenes significantly enhance Interlaminar Shear Strength (ILSS), flexural modulus, and fracture toughness even at ultra-low concentrations through mechanisms such as crack deflection, bridging, and mechanical interlocking. Notably, interfacial modifications in UHMWPE composites have demonstrated a reported increase in Interfacial Shear Strength (IFSS). Beyond mechanical gains, MXenes provide multifunctional capabilities, including electromagnetic interference shielding and superior resistance to corrosive environments. This study concludes that, despite being an emerging area, the synergy between MXenes and fiber-reinforced epoxy polymers represents a promising approach for the development of next-generation multifunctional composites with high durability.

Keywords: Fiber-reinforced epoxy, MXenes, Nanosheets

Introduction

Composite materials are engineered structures formed by combining two or more components that remain insoluble within each other at the macroscopic level. This combination results in properties superior to those of the individual constituents. Specifically, Fiber-Reinforced Polymer Composites (FRPCs) have replaced traditional metallic materials in critical engineering sectors - such as aerospace, automotive, and defense - due to their lightweight nature, high specific strength, and excellent corrosion resistance. In these systems, the matrix phase binds the reinforcement elements together and facilitates load transfer to the fibers, while the fibers act as the primary load-bearing components, providing strength and stiffness (Guzel & Onal, 2025).

MXenes represent a novel family of two-dimensional (2D) transition metal carbides, nitrides, or carbonitrides with a graphene-like structure. These materials are synthesized by the selective etching of precursor ceramics known as MAX phases, which have the general formula $M_{n+1}AX_n$. In this formula, M represents early transition metals (e.g., Ti, V, Nb), A denotes elements from groups 13 (IIIA) or 14 (IVA) of the periodic table (typically Al or Si), and X stands for carbon or nitrogen (Gan & Xiong, 2025).

During the synthesis process, the A layers are selectively removed and replaced by functional groups which impart a hydrophilic character to the surface. A defining feature of MXenes, distinguishing them from other nanomaterials, is their combination of high metallic conductivity and the ability to form chemical bonds with polymer matrices via these functional groups. Technically, MXenes exhibit an extraordinary Young's modulus, making them ideal candidates for structural composite reinforcement. Furthermore, their high specific surface area allows them to function as multifunctional bridging agents that enhance mechanical interlocking at the interface (Pan et al., 2026).

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The integration of MXenes into FRPCs offers the potential to simultaneously enhance mechanical strength, electrical conductivity, and thermal stability. Due to their active surface functional groups, MXenes establish strong interactions between the matrix and the fibers, maximizing load transfer efficiency and minimizing interfacial weaknesses. Additionally, the superior metallic conductivity of MXenes enables the development of multifunctional composites with advanced capabilities, such as Electromagnetic Interference (EMI) shielding and structural health monitoring (self-sensing).

MXene Synthesis Mechanisms and Preparation Methods

The performance of MXene-based structural materials fundamentally depends on the efficiency of the exfoliation process from the MAX phase. In $M_{n+1}AX_n$ phases, the M-A bonds are metallic in nature and significantly weaker than the ionic/covalent M-X bonds. This difference in bond energy allows for the selective removal of A elements using appropriate chemical etchants (Aghamohammadi et al., 2021).

The resulting MXene surfaces are terminated with hydroxyl (-OH), oxygen (-O), and fluorine (-F) groups. These terminal groups dictate the hydrophilic nature and the electrical/mechanical properties of the material. While various techniques - including molten salt etching, alkali-assisted hydrothermal methods, and electrochemical etching - have been developed, two primary methods currently dominate due to their yield and control.

Direct HF Method

The direct HF etching method is one of the common top-down protocols that involves the selective removal of the A group (usually Al) from the MAX phase (Zhao et al., 2019). The protocol is briefly as follows:

MAX phase powder is slowly added to a high-concentration HF solution (typically 40-48 wt%). The reaction is performed in a PTFE beaker at room temperature to manage the exothermic nature of the process. Reaction times typically involve 24 hours of continuous magnetic stirring. A atoms react with the acid to form soluble salts, leaving behind an accordion-like multilayered MXene structure. The suspension is then centrifuged (e.g., 5000 rpm) and washed repeatedly with deionized water until the supernatant reaches a pH of approximately 6.

Several key studies in the literature demonstrate the versatility of the direct HF method in enhancing composite performance. Ding et al. (2021) synthesized Ti_2C MXene nanosheets from Ti_2AlC MAX phase via HF etching and successfully grafted these layers onto carbon fiber surfaces to improve the interfacial properties of epoxy composites. Similarly, Zhao et al. (2019) synthesized $Ti_3C_2T_x$ MXene through HF etching followed by sonication, subsequently coating the resulting nanosheets onto carbon fibers using an electrostatic self-assembly method to enhance the mechanical performance of the epoxy resin. In a more recent application, Kumar et al. (2025) synthesized multilayer MXene by stirring 1g of Ti_3AlC_2 powder in 20 mL of 48% HF solution for 24 hours at room temperature; the product was then modified with silane to improve EMI shielding properties within the epoxy matrix. Furthermore, Pei et al. (2025) utilized 40 mL of HF to etch 2 g of Ti_3AlC_2 powder over a 24 hours reaction period, loading the synthesized MXene onto carbon fiber surfaces to synergistically develop the tribological properties, including wear and friction resistance, of the resulting epoxy composites.

The direct HF method is characterized by several distinct advantages and disadvantages that influence its selection for MXene synthesis. On the positive side, it offers high efficiency in completely removing the A layer from the MAX phase, yielding high-purity multilayer structures. It also features a relatively short reaction time compared to alternative techniques, making it the standard protocol for large-scale production. Moreover, the method results in a distinct accordion-like morphology, which provides a significantly increased surface area that is highly beneficial for various reinforcement applications. Conversely, the method presents significant safety risks, as HF is extremely toxic and corrosive, requiring specialized PTFE equipment and stringent laboratory safety protocols. The aggressive nature of the acid may also induce structural defects or vacancies within the MXene layers. Finally, there is an additional processing requirement, as the resulting product is typically multilayered and necessitates a separate delamination step using chemicals to achieve single-layer separation (Ding et al., 2021).

MILD Method

The Minimally Intensive Layer Delamination (MILD) method avoids direct HF use by generating HF in-situ through the reaction: $LiF + HCl \rightarrow HF + LiCl$ (Liu et al., 2019). The protocol is briefly as follows:

LiF is dissolved in concentrated HCl (6M-12M), followed by the slow addition of MAX phase powder. The reaction is typically conducted at mild temperatures (35-40°C) for 24 to 48 hours. A key advantage of this method is the simultaneous intercalation of Li⁺ ions between MXene layers during etching. This expands the interlayer spacing and weakens Van der Waals forces. Upon reaching pH 6 through washing, the resulting clay-like sediment can be delaminated into single or few-layer colloidal suspensions through simple manual shaking or low-energy sonication.

The effectiveness of the MILD method in producing high-quality MXenes is evidenced by several recent studies across diverse composite systems. Yuksel Yilmaz et al. (2024) investigated the integration of 2D nanofillers synthesized via the MILD method into aerospace-grade epoxy composites, highlighting how the resulting high structural integrity significantly enhances both mechanical damping and electrical conductivity. Similarly, Wang et al. (2023) demonstrated that MILD-synthesized and surface-modified MXenes achieve exceptional homogeneous dispersion within the epoxy matrix reinforced with Ultra High Molecular Weight Polyethylene (UHMWPE) fibers, resulting in a substantial increase in Interfacial Shear Strength (IFSS).

Regarding matrix compatibility and functional thresholds, Qian et al. (2022) analyzed the electrical percolation behavior of these nanosheets in epoxy, revealing that the surface hydroxyl groups inherent to the MILD process are instrumental in optimizing matrix-filler synergy. For tribological applications, Song et al. (2024) showed that hybridizing MILD-produced MXenes with TiO₂ nanodot modifications significantly improves the wear and friction resistance of epoxy resins. Furthermore, the role of MXenes in advanced diagnostics was explored by Hu et al. (2025), who utilized MXene/polyurethane (PU) modifications for in-situ damage sensing in Carbon Fiber-Reinforced Composites (CFRCs); they noted that the high conductivity afforded by the MILD synthesis is critical for the precision of electrical signal measurements. Finally, Qu et al. (2025) supported these findings by illustrating how MILD-MXene layers effectively guide crack deflection within the epoxy matrix, thereby enhancing energy dissipation mechanisms as confirmed through rigorous mechanical testing.

The MILD method is increasingly favored due to several technical benefits, beginning with enhanced safety; the life-threatening risks and corrosive hazards of direct concentrated HF are significantly mitigated through precise acidity control. This method also produces high-quality flakes that better preserve the lateral size of the nanosheets and minimize structural defects compared to the HF method. A distinctive advantage is spontaneous delamination, as the intercalation of Li⁺ ions during etching allows for layer separation without the need for toxic chemicals or high-intensity sonication.

Furthermore, MILD-synthesized MXenes exhibit superior colloidal stability in water, facilitating a more homogeneous dispersion within epoxy resins and other polymer matrices. However, the method requires a longer reaction time, generally spanning 24-48 hours. There is also a risk of residual impurities, specifically LiCl, remaining between the layers if the washing process is not performed meticulously, which can negatively impact the final composite's dielectric and thermal performance (Liu et al., 2021).

Table 1. Technical comparison of MXene synthesis methods

Feature	Direct HF Method	MILD Method
Etching Agent	Concentrated Hydrofluoric Acid (40-48%)	In-situ generated HF (LiF/HCl)
Safety Level	Low (High toxicity and corrosive risk)	Moderate (Lower acid concentration, safer handling)
Reaction Time	Generally shorter (24 hours)	Longer (24-48 hours)
Delamination	Requires separate intercalants	Spontaneous delamination via Li ⁺ ions
Nanosheet Quality	Potential for more structural defects	Higher quality, larger lateral size, fewer defects
Morphology	Distinct accordion-like multilayer	Clay-like sediment, easier single-layer yield
Colloidal Stability	Moderate (Requires intensive processing)	High (Superior stability in aqueous media)
Environmental Impact	High due to hazardous waste	Moderate; more controlled acidity

A comparative analysis of these two dominant synthesis routes, focusing on safety, structural integrity, and exfoliation efficiency, is summarized in Table 1. As indicated in the table, the selection of the synthesis route is a critical decision that balances the structural integrity of the flakes against the scalability and safety of the process.

Intercalation and Delamination

The transition from accordion-like multilayer MXene to single nanosheets depends heavily on the chosen synthesis route. In the Direct HF method, post-synthesis intercalation using external organic molecules is mandatory to weaken interlayer bonds. Conversely, the MILD method facilitates in-situ intercalation, where Li^+ ions from the etchant integrate between the layers during the reaction itself. Following these steps, applicable to both methodologies, sonication provides the necessary energy to overcome remaining Van der Waals forces. Literature suggests processing the pH-neutral suspension in an ultrasonic bath for 1.5 to 2 hours. To prevent oxidation, this process must be conducted in an ice bath, ideally under argon gas protection. The final colloidal solution is centrifuged to remove un-exfoliated particles, resulting in high-quality single or few-layer MXene nanosheets (Yilmaz et al., 2024a). The successful exfoliation and stabilization of these nanosheets are prerequisite steps for their effective integration into polymer matrices, where their reinforcing potential varies depending on the type of fiber reinforcement employed.

Performance Analysis of Fiber-Reinforced Epoxy Polymers

This section evaluates various studies focusing on the integration of MXenes into FRPCs through the direct incorporation of these nanosheets into the epoxy resin matrix. The analysis covers the mechanical, interfacial, and multifunctional impacts of MXene modification across four primary reinforcement types: carbon, glass, basalt, and UHMWPE fibers. Detailed findings regarding the synergistic effects of MXenes on these diverse composite systems are presented in the following sections. Carbon Fiber-Reinforced Polymers (CFRPs) are the benchmark for high-performance structural materials; however, their performance is often limited by poor interlaminar properties. The high aspect ratio and surface functionality of MXenes provide a strategic solution to enhance the fiber-matrix interface in these systems.

Duan et al. (2024b) investigated the mechanical performance of Carbon Fiber-Reinforced Epoxy Composites (CFRECs) modified with $\text{Ti}_3\text{C}_2\text{T}_x$ MXene nanosheets. The nanosheets were dispersed into the epoxy resin via a co-blending process, and multilayer composites were subsequently fabricated through layer-by-layer assembly and hot pressing. The results demonstrated that the interlaminar shear strength (ILSS) improved significantly as MXene content increased, achieving a 17.27% enhancement at a 2 wt% loading. This mechanical improvement was attributed to the formation of a strengthened MXene/epoxy matrix layer and the ability of the 2D nanosheets to effectively hinder crack propagation within the interlaminar region. In a other study, Duan et al. (2024a) explored the impact of introducing MXene as a reinforcing phase at both the fiber-matrix interface and within the epoxy matrix. By depositing 0.5 wt% MXene onto the carbon fiber fabric via atomization and dispersing additional MXene into the matrix, the researchers achieved a remarkable 55.58% increase in ILSS. This synergistic reinforcement was credited to improved mechanical interlocking, hydrogen bonding, and Van der Waals interactions at the interface. Furthermore, the crack-bridging effect provided by the MXene nanosheets within the matrix further fortified the composite against structural failure.

Song et al. (2025) examined the mechanical and multifunctional properties of short CFRECs modified with MXene. The short carbon fibers were first functionalized with nitric acid and then coated with MXene layers to create a heterostructured MXene/short carbon fibers reinforcement phase. At an optimum fiber-to-MXene ratio, the flexural strength increased to 113.9 MPa and impact strength reached 18.0 kJ/m², representing significant mechanical gains. These improvements were driven by increased surface roughness and strong interfacial bonding, while the study also briefly noted enhanced thermal conductivity and reduced wear rates due to the MXene's lubricious nature. Qu et al. (2025) focused on the mechanical and interfacial properties of MXene-dispersed carbon fiber reinforced epoxy composites at both room temperature and cryogenic temperatures (90°K). The incorporation of just 0.10 wt% MXene resulted in a 13.03% increase in ILSS and a 26.84% boost in Mode-II interlaminar fracture toughness at cryogenic levels. The researchers identified that MXene functional groups facilitate bridging and mechanical interlocking, which are critical for preventing thermal stress-induced microcracking. The study also confirmed a reduction in the coefficient of thermal expansion as a secondary benefit of the modification.

Qin et al. (2025) utilized polydopamine-functionalized MXene nanosheets within an epoxy vitrimer resin to produce bidirectional carbon fiber composites. While the matrix-level tensile and flexural strengths showed a slight decline due to the vitrimer chemistry, the composite-level ILSS increased from 52.1 MPa to 58.5 MPa upon MXene addition. This enhancement was explained by the formation of hydrogen bonds between the matrix and the amine/phenolic hydroxyl groups on the MXene nanosheet, which increased the interfacial contact area. The research also highlighted secondary improvements in thermal stability, flame retardancy, and self-healing

capabilities. Kumar et al. (2025) incorporated silane-modified MXene directly into the epoxy matrix to improve the mechanical and EMI shielding performance of CFRPs. The results revealed that silane-modified MXene provided substantial gains, including a 40% increase in tensile strength, a 30% increase in flexural strength, and a 34.21% rise in short beam strength. The amine groups introduced via silane established covalent bonds with the epoxy, increasing cross-linking density and enabling crack pinning and bridging mechanisms. Beyond mechanical reinforcement, the study emphasized the material's superior EMI shielding efficiency.

Hu et al. (2025) presented a hybrid filler system consisting of 0.1 wt% MXene and 1 wt% PU to enhance the mechanical and damage-sensing performance of CFRPs. The hybrid composite achieved an extraordinary 104% increase in flexural strength and a 79% increase in ILSS, reaching values of 885.7 MPa and 52.2 MPa, respectively. This dramatic improvement resulted from the MXene's 2D morphology causing crack deflection and the PU increasing ductility through hydrogen bonding. The study also noted that the interconnected network formed by these fillers provided a baseline for advanced in-situ damage sensing. Pei et al. (2025) investigated the synergistic effects of loading MXene onto carbon fiber surfaces within a hybrid epoxy matrix containing a rubber phase. While the primary focus was on tribology, the research demonstrated that carbon fibers bear the structural load while MXene nanosheets prevent deep matrix wear. The configuration led to a 55.8% reduction in the friction coefficient and a 96.6% decrease in the wear rate. This study confirms that MXene serves as a dual-purpose additive, acting as an effective solid lubricant while maintaining the structural integrity provided by the carbon fibers. Hu et al. (2025) explored the potential of hydroxylated MXene as a nano-binder to reinforce interfacial bonding and enhance the toughness the matrix in CFRP laminates. By adding only 0.1 wt% hydroxylated MXene, the flexural strength and ILSS increased by 52.9% and 40%, respectively, surpassing the performance of much higher concentrations of carbon nanotube (CNT) or graphene. The primary mechanism involved hydroxylated MXene forming a 3D network that redistributed loads and induced crack branching, which effectively prevented brittle failure. The study highlighted a 62.6% increase in fracture energy, suggesting high resistance to fatigue and impact. Glass fibers provide excellent electrical insulation and cost-effectiveness; however, they often encounter challenges such as moisture absorption and moderate mechanical strength. Consequently, recent research has focused on incorporating MXenes, particularly in hybrid configurations, to bridge these performance gaps.

Priyadarshini et al. (2023) conducted a comparative study on the effects of MXene and graphene within hybrid E-glass and hemp fiber epoxy composites, focusing on the dominant influence of MXene on mechanical and physical properties. Through the application of hand lay-up and vacuum bagging techniques, it was observed that incorporating 1 wt% MXene into the matrix led to a substantial 45% increase in flexural strength and an 11.2% enhancement in tensile strength compared to the neat hybrids. This performance leap is attributed to terminal functional groups on the MXene flakes that stabilize load distribution between the fiber and matrix while increasing rigidity to delay sudden failure. Furthermore, MXene-modified composites exhibited nearly 50% lower water absorption than graphene-based counterparts, proving MXene's role as a superior moisture barrier and environmental stabilizer. Bodduru et al. (2023) investigated the use of MXene, graphene nanoplatelets, and CNTs to enhance the mechanical performance and environmental resistance of sisal/glass fiber hybrid epoxy composites. The results indicated that adding MXene to the hybrid system increased tensile strength from 47 MPa to 67.1 MPa and flexural strength from 64.7 MPa to 86.3 MPa, nearly recovering the baseline performance of pure glass fiber composites. This success is credited to the high 2D surface area of MXene, which facilitates robust mechanical interlocking and efficient stress transfer between the matrix and fibers. Notably, MXene also reduced the void ratio from 17.2% to 10.3%, suggesting improved resin flow and fiber wettability during fabrication, while simultaneously increasing elongation at break by 37%. Tadesse et al. (2025) examined the water resistance and structural stability of hemp/glass fiber hybrid composites modified with MXene and graphene nanofillers. While glass fibers inherently reduce water absorption compared to natural fibers, the study found that MXene plays a critical protective role as a chemical shield in aggressive acidic (HCl) and alkali (NaOH) environments. In these harsh conditions, MXene exhibited superior chemical stability compared to graphene, effectively minimizing matrix degradation and subsequent moisture intake. Fourier-Transform Infrared Spectroscopy (FTIR) analysis confirmed the presence of hydrogen bonding between the fibers and matrix, which, combined with the low porosity provided by the glass fibers, makes these composites highly suitable for marine and heavy industrial applications. Yilmaz et al. (2024b) explored the use of pristine MXene and silane-functionalized MXene to simultaneously improve the mechanical and flame-retardant properties of glass fiber-reinforced epoxy composites. The highest mechanical gains were achieved at a 0.25 wt% loading, where silane-functionalized MXene composites showed a 27.55% increase in flexural strength, a 19.21% increase in tensile strength, and a 12.40% increase in ILSS. The silane coupling agent significantly improved the dispersion of nanosheets and established strong chemical bonds between the epoxy and the MXene flakes. Additionally, the functionalized MXene acted as an effective fire retardant, reducing the burn rate by 25.50% at 0.5 wt% loading, confirming its dual strategic value as a structural and safety-oriented additive.

Basalt fibers are gaining prominence as eco-friendly alternatives to glass fibers, yet their susceptibility to chemical degradation in alkaline environments remains a critical concern. MXenes serve as a dual-purpose additive in basalt-reinforced epoxy, acting as both a mechanical reinforcement and a chemical barrier. Qian et al. (2022) studied a hybrid nanofiller system composed of 2D MXene and CNTs to enhance the mechanical performance and corrosion resistance of Basalt Fiber-Reinforced Polymer (BFRP) composites. The research highlighted a synergistic bridging effect, where CNTs prevent the MXene layers from restacking, creating a nano-rivet network within the polymer matrix. This configuration led to a 53.5% increase in tensile strength and a 43.2% increase in flexural strength compared to pristine BFRP. Most significantly, after 120 days of alkali immersion, the MXene/CNT-modified samples showed negligible changes in mechanical properties, proving that the hybrid barrier tightly encapsulates the basalt fibers to prevent environmental corrosion. Qian et al. (2023) focused on mitigating the poor alkali resistance of BFRPs by incorporating MXene nanosheets into the matrix via the vacuum-assisted resin transfer molding process. At a loading of 0.5 wt%, the flexural strength reached 530.1 MPa, marking a 39.4% improvement due to optimized stress transfer and more tortuous crack propagation paths. In harsh alkali aging tests at 40°C for 60 days, the MXene-reinforced samples maintained structural integrity that was surprisingly higher than that of pristine, unaged BFRP. This superior durability is attributed to a combination of the physical 2D barrier effect, which creates a tortuous path and an increased cross-linking density in the epoxy matrix induced by MXene surface functional groups.

UHMWPE fibers possess extraordinary specific strength but suffer from inherently low surface energy, leading to poor interfacial adhesion with epoxy resins. MXene-based surface modifications offer a promising route to induce chemical reactivity on these inert fiber surfaces. Wang et al. (2023) developed an organic-inorganic hybrid MXene to overcome the inherently poor interfacial adhesion of UHMWPE fibers in epoxy matrices. By chemically modifying MXene with silane, the researchers created a filler that achieves both homogeneous matrix dispersion and strong covalent bonding at the fiber interface. The results were dramatic, with the IFSS increasing by 324% (from 2.13 MPa to 9.04 MPa) and tensile strength rising by 56% to reach 142.7 MPa. The organic phase of the hybrid MXene acts as a stress-absorbing buffer, while the inorganic hybrid MXene phase provides high-strength mechanical resistance. Scanning Electron Microscope (SEM) and micro-bond tests confirmed that this modification shifts the failure mode from simple adhesive separation to a complex process involving crack branching and enhanced energy dissipation.

Summary and Outlooks

This review has comprehensively evaluated recent investigations into the transformative effects of MXenes on the mechanical, tribological, thermal, corrosion, and electrical performance of FRPCs. The summarized literature indicates that MXenes, even at exceptionally low loadings (typically 0.1 to 1 wt%), lead to substantial improvements across all investigated properties. The primary mechanism for these mechanical gains is the presence of active functional groups (-OH, -O, -F) on the MXene surface, which facilitate hydrogen bonding, covalent cross-linking, and superior interfacial load transfer. Furthermore, the 2D layered morphology provides a physical barrier that induces crack deflection and pinning, while also forming self-lubricating transfer films that dramatically reduce wear rates. Despite the significant progress observed in recent years, the application of MXenes in advanced structural composites remains a burgeoning field with several unexplored avenues. Future research should prioritize the following directions to unlock the full potential of these materials:

- While $\text{Ti}_3\text{C}_2\text{T}_x$ is widely studied, other transition metal carbides such as Ti_2CT_x and Nb_2CT_x should be investigated for specific aerospace and defense applications.
- Comprehensive research is needed to directly compare MXenes against other two-dimensional (2D) nanomaterials, such as graphene, molybdenum disulfide (MoS_2), and boron nitride (BN), within identical polymer systems to establish clear performance benchmarks.
- To establish advanced multi-scale reinforcement networks, it is necessary to conduct deeper research into the synergy between MXenes and complementary nano-forms, including 1D carbon nanotubes and 0D nanodots.
- There is a critical need for advanced analytical modeling and molecular dynamics simulations to predict the interfacial behavior and failure mechanisms of various MXene-reinforced fiber systems.

Scientific Ethics Declaration

* The author declares that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the author.

Conflict of Interest

* The author declares that there is no conflict of interest.

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Author(s) Information

Muhammed Huseyin Guzel

Technical Sciences Vocational School

Konya Technical University, Konya, Türkiye

ORCID iD: <https://orcid.org/0000-0003-3093-3453>

*Contact e-mail: mhguzel@ktun.edu.tr

*Corresponding author(s) contact email

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DSOGI-PLL and Moving Average Filter Based Control Method for Shunt Active Power Filter

Ali Sait Ozer

Konya Technical University

Abstract: The increasing penetration of nonlinear loads and power electronic converters in modern power systems has led to a significant rise in current harmonics and power quality problems. The shunt active power filter (SAPF) has emerged as an effective solution to mitigate these issues. However, the performance of SAPF systems largely depends on the accuracy of the reference current generation method and the effectiveness of the synchronization algorithm. In conventional synchronous reference frame (SRF- dq) based SAPF control methods, low-pass filters (LPFs) are commonly used to extract the fundamental component, while high-pass filters (HPFs) are employed to obtain harmonic components. Nevertheless, these filtering structures may introduce undesirable effects such as time delay and phase shift, which degrade the dynamic performance of the control system. In this study, an improved dq -based control strategy is proposed for SAPF applications by combining a Dual Second-Order Generalized Integrator Phase-Locked Loop (DSOGI-PLL) based synchronization technique with a Moving Average Filter (MAF) based harmonic extraction approach. In the proposed method, the DSOGI-PLL structure ensures accurate phase angle estimation even under distorted grid conditions, while the MAF structure enables the extraction of the fundamental current component without introducing the delay and phase shift problems associated with conventional LPF and HPF filters. The effectiveness of the proposed control method is evaluated through simulation studies under different operating conditions. In the case of sinusoidal grid voltage and nonlinear load, the total harmonic distortion (THD) of the source current is reduced from approximately 19.19% to 0.79%. Furthermore, under distorted grid voltage and nonlinear load conditions, the source current THD values decrease to the range of 1.55–1.89%. These results demonstrate that the proposed method significantly enhances harmonic mitigation performance and ensures compliance with the limits specified in the IEEE 519-2014 standard.

Keywords: Dual second-order generalized integrator (DSOGI), Harmonic mitigation, Moving average filter (MAF), Power quality, Shunt active power filter (SAPF)

Introduction

The increasing integration of power electronic converters and nonlinear loads in modern power systems has led to a significant rise in power quality problems such as current harmonics, voltage distortions, and reduced power factor (Özer et al., 2026). These undesirable effects may cause overheating in electrical equipment, malfunction of sensitive devices, additional power losses, and a decrease in overall system efficiency. Therefore, harmonic mitigation and power quality improvement have become critical issues in distribution networks (Sant, Patel et al. 2024).

Traditionally, passive filters composed of inductors and capacitors have been utilized to reduce harmonic components (Rath et al., 2024). Although passive filters offer a simple and low-cost solution, they suffer from several major drawbacks, including fixed compensation capability, bulky structure, and the possibility of resonance with grid impedance. Consequently, passive filters cannot always provide satisfactory performance under varying operating conditions (Sundaram & Venugopal 2016).

With the advancements in power electronics and digital control technologies, active power filters (APFs) have emerged as an effective solution for mitigating harmonics and improving power quality. Among the different types of active power filters, the shunt active power filter (SAPF) is widely employed to suppress current harmonics generated by nonlinear loads (Wu et al., 2024). The performance of SAPF systems largely depends on the accuracy of the reference current generation technique and the effectiveness of the synchronization algorithm (Sundaram & Venugopal 2016).

Various approaches have been proposed in the literature for reference current generation, including the instantaneous power theory (p-q theory) and the synchronous reference frame (SRF), also referred to as the dq theory (Özer & Karaca). However, the p-q theory may exhibit limited performance under unbalanced and distorted grid voltage conditions, as it may fail to generate an accurate reference current (Amini, Rastegar et al. 2024). In contrast, the SRF-based control approach has been widely adopted due to its simple structure and fast dynamic response.

Nevertheless, in conventional SRF-based control methods, low-pass filters (LPFs) are typically used to extract the fundamental component, whereas high-pass filters (HPFs) are employed to obtain harmonic components. The use of LPFs may introduce delays that slow down the dynamic response of the system (Çelik, Ahmed et al. 2022), whereas HPFs may cause phase shifts that adversely affect system stability and the accuracy of the reference current generation (Hmad et al., 2025).

Another critical issue in SRF-based SAPF control is the accurate estimation of the grid phase angle required for coordinate transformations. In grid-connected power electronic systems, phase-locked loop (PLL) structures are widely employed for synchronization purposes. Although the conventional SRF-PLL structure provides satisfactory performance under ideal grid conditions, its performance significantly deteriorates in the presence of harmonic distortion in grid voltages (Sevilmiş & Karaca 2019). To overcome these limitations, several advanced PLL structures have been proposed in recent years. Among them, the dual second-order generalized integrator based PLL (DSOGI-PLL) has attracted considerable attention due to its ability to provide more accurate phase and frequency estimation under distorted grid conditions (Sevilmiş & Karaca 2022).

In this study, an improved SAPF control strategy is proposed by combining a DSOGI-PLL-based synchronization technique with a moving average filter (MAF)-based harmonic extraction approach. In the proposed method, the DSOGI-PLL structure enables accurate phase angle estimation even under harmonic-contaminated grid conditions, while the MAF structure allows the fundamental current component to be extracted without introducing the delay and phase shift problems commonly associated with conventional LPF and HPF filters. Consequently, the proposed control strategy aims to enhance harmonic compensation performance and reduce the total harmonic distortion (THD) of the source current.

The effectiveness of the proposed method is evaluated through simulation studies conducted under different operating scenarios, including sinusoidal grid voltage with harmonic load and distorted grid voltage with nonlinear load conditions. The results obtained demonstrate that the proposed approach achieves lower THD values compared to conventional methods, thereby improving harmonic mitigation performance. Furthermore, the resulting THD values remain below the 5% limit specified in the IEEE 519-2014 standard, indicating that the proposed method provides an effective solution for improving power quality in distribution systems.

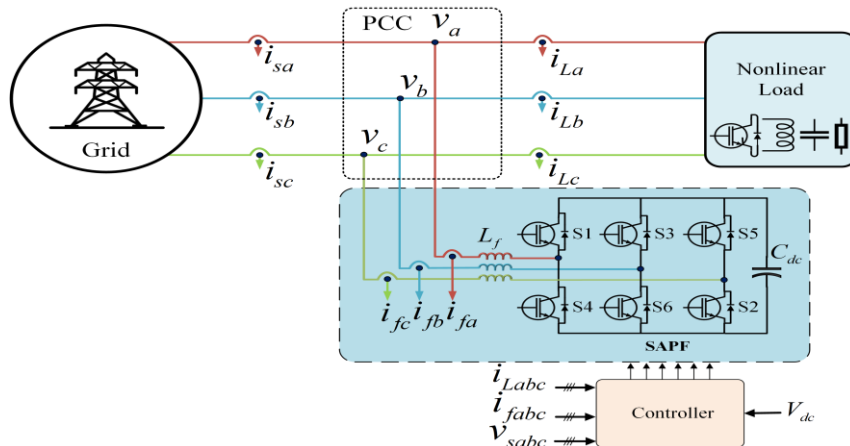


Figure 1. System configuration of the SAPF connected to the grid and nonlinear load.

Modeling of Shunt Active Power Filter

The schematic configuration of the SAPF system connected to the grid and nonlinear load is illustrated in Figure 1. The SAPF operates as a controlled current source that generates compensating currents with the same magnitude but opposite phase to the harmonic currents produced by the nonlinear load. By injecting these compensating currents at the point of common coupling (PCC), the harmonic components in the source current are effectively suppressed, allowing the source current to approach a sinusoidal waveform.

In this study, the SAPF structure consists of a voltage source inverter (VSI) connected in parallel with the distribution system, an interfacing inductor L_f , and a DC-link capacitor C_{dc} . The VSI is composed of six bidirectional semiconductor switches, which can be implemented using power electronic devices such as IGBTs, MOSFETs, or GTOs, depending on the power level of the application. The switching operation of the inverter is controlled by the signals generated from the control algorithm, enabling the SAPF to inject the required compensating currents into the system.

Improved dq -based control strategy for SAPF

In this study, an improved dq -based control strategy is proposed to enhance the harmonic compensation performance of SAPF under distorted grid conditions. The overall block diagram of the proposed control scheme is illustrated in Figure 2. The proposed structure combines a DSOGI-PLL-based synchronization unit with a moving average filter (MAF)-based fundamental component extraction method. While the DSOGI-PLL structure provides accurate phase angle estimation under distorted grid conditions, the MAF enables effective extraction of the fundamental current component in the dq reference frame. The main components and operating principles of the proposed control scheme are explained in detail in the following subsections.

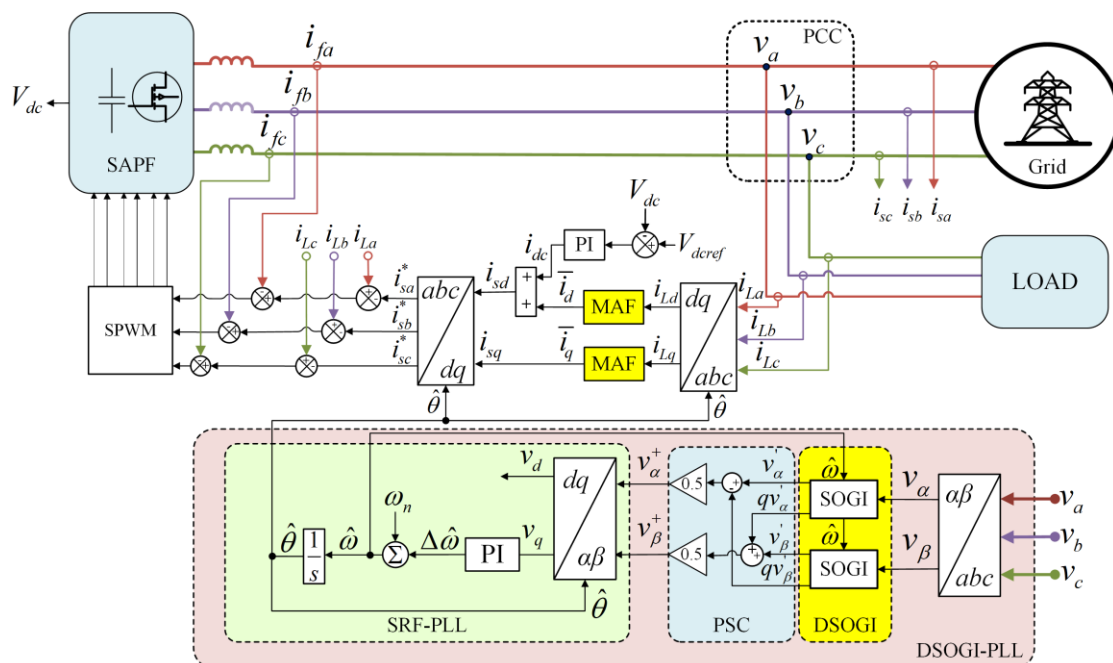


Figure 2. Block diagram of the proposed dq -based control strategy for SAPF.

DSOGI-PLL Configuration

Figure 2 shows the overall block diagram of the proposed dq -based control strategy for SAPF. In this control scheme, the DSOGI-PLL unit is used to obtain the grid phase angle, which is required for the coordinate transformations. Within the DSOGI-PLL structure, two second-order generalized integrators (SOGIs) are employed to suppress unwanted harmonic components present in the v_α and v_β signals. Each SOGI produces both a filtered version of the input signal and its corresponding quadrature (90° phase-

shifted) component. In this context, qv'_α and qv'_β represent the quadrature components of v'_α and v'_β respectively. The transfer functions of the SOGI can be expressed as given in Rodriguez et al. (2006).

$$R(s) = \frac{v'_{\alpha,\beta}}{v_{\alpha,\beta}} = \frac{k\hat{\omega}s}{s^2 + k\hat{\omega}s + \hat{\omega}^2} \quad (1)$$

$$Q(s) = \frac{qv'_{\alpha,\beta}}{v_{\alpha,\beta}} = \frac{k\hat{\omega}^2}{s^2 + k\hat{\omega}s + \hat{\omega}^2} \quad (2)$$

In this expression, the parameters k and $\hat{\omega}$ correspond to the damping coefficient and the estimated angular frequency, respectively. As illustrated in Fig. 5, the outputs of the SOGI blocks are forwarded to the positive sequence calculator (PSC) to obtain the positive sequence components of the v_α and v_β signals, denoted as v_α^+ and v_β^+ . The PSC module is implemented based on the instantaneous symmetrical component theory, and its operation follows the formulation presented in (Golestan, Monfared et al. 2012).

$$\begin{bmatrix} v_\alpha^+ \\ v_\beta^+ \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 & -q \\ q & 1 \end{bmatrix} \begin{bmatrix} v'_\alpha \\ v'_\beta \end{bmatrix} \quad (3)$$

The extracted signals v_α^+ and v_β^+ are subsequently processed by a conventional SRF-PLL to estimate the phase angle, amplitude, and frequency of the input voltages. The estimated frequency is then fed back to the SOGI blocks, allowing the DSOGI-PLL structure to adapt to variations in the grid frequency.

MAF Structure

The LPFs employed for filtering i_{Ld} and i_{Lq} present two major drawbacks: they introduce phase delay and are not capable of effectively attenuating harmonic components generated by nonlinear and unbalanced loads. To overcome these limitations, a moving average filter (MAF) is adopted in this study instead of conventional LPFs, as illustrated in Figure 2. Due to its simple structure and ease of implementation, the MAF has recently gained considerable attention in power electronic control applications (Özer, Sevilmiş et al. 2022).

Under specific conditions, the moving average filter (MAF) can exhibit a behavior similar to that of an ideal low-pass filter (LPF). The transfer functions of the MAF in the s -domain and z -domain can be represented as follows (Golestan, Ramezani et al. 2013).

$$\text{MAF}(s) = \frac{1 - e^{-T_\omega s}}{T_\omega s} \quad (4)$$

$$\text{MAF}(z) = \frac{1}{N} \frac{1 - z^{-N}}{1 - z^{-1}} \quad (5)$$

In these expressions, T_ω and N represent the window length of the MAF and the filter order, respectively. The filter order N is defined as $f_s T_\omega$, where f_s denotes the sampling frequency. Based on (5), the digital implementation of the MAF can be derived, and its block diagram is presented in Figure 3. Owing to its simple structure, the MAF enables an efficient and straightforward implementation in SAPF control schemes based on the dq -theory.

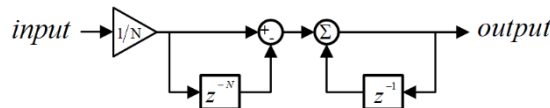


Figure 3. Block diagram of MAF for digital implementation.

***dq*-Based Reference Current Generation**

The synchronous reference frame (*dq*) method is widely used in shunt active power filter (SAPF) applications due to its simple structure and fast dynamic response. In this method, the three-phase load currents are transformed into a rotating reference frame where the fundamental component appears as a DC value while harmonic components appear as oscillating quantities. The three-phase load currents i_{La} , i_{Lb} , and i_{Lc} are transformed into the synchronous reference frame using the Park transformation as

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos \hat{\theta} & \cos(\hat{\theta} - \frac{2\pi}{3}) & \cos(\hat{\theta} + \frac{2\pi}{3}) \\ \sin \hat{\theta} & -\sin(\hat{\theta} - \frac{2\pi}{3}) & -\sin(\hat{\theta} + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (6)$$

where $\hat{\theta}$ represents the grid phase angle obtained from the DSOGI-PLL synchronization unit.

The obtained *dq*-axis currents contain both fundamental and harmonic components. To extract the fundamental component of the load currents, a moving average filter (MAF) is applied to the *dq*-axis currents. The filtered signals are expressed as

$$\bar{i}_d = MAF(i_{Ld}) \quad (7)$$

$$\bar{i}_q = MAF(i_{Lq}) \quad (8)$$

These filtered components represent the fundamental components of the load current in the synchronous reference frame. In addition to harmonic compensation, the DC-link voltage of the voltage source inverter must be maintained at a constant level to ensure proper operation of the SAPF. For this purpose, the measured DC-link voltage V_{dc} is compared with the reference value V_{dcref} , and the resulting error signal V_{dcer} is processed through a PI controller to generate the active current component i_{loss} :

$$i_{dc(n)} = i_{dc(n-1)} + K_{pd(n)}(V_{dcer(n)} - V_{dcer(n-1)}) + K_{id(n)}V_{dcer(n)} \quad (9)$$

The reference current components in the *dq* frame are then obtained as

$$i_{sd} = \bar{i}_d + i_{dc} \quad (10)$$

$$i_{sq} = \bar{i}_q \quad (11)$$

After calculating the reference currents in the *dq* frame, the three-phase reference source currents are obtained using the inverse Park transformation

$$\begin{bmatrix} i_{sa}^* \\ i_{sb}^* \\ i_{sc}^* \end{bmatrix} = \begin{bmatrix} \cos \hat{\theta} & -\sin \hat{\theta} \\ \cos(\hat{\theta} - \frac{2\pi}{3}) & -\sin(\hat{\theta} - \frac{2\pi}{3}) \\ \cos(\hat{\theta} + \frac{2\pi}{3}) & -\sin(\hat{\theta} + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} \quad (12)$$

In order to determine the compensating current required from SAPF, the reference source currents are subtracted from the measured load currents. In this way, the reference filter currents that must be injected by the SAPF are obtained. These reference currents are then compared with the measured filter currents, and the resulting error signals are used to generate the PWM switching pulses for the voltage source inverter.

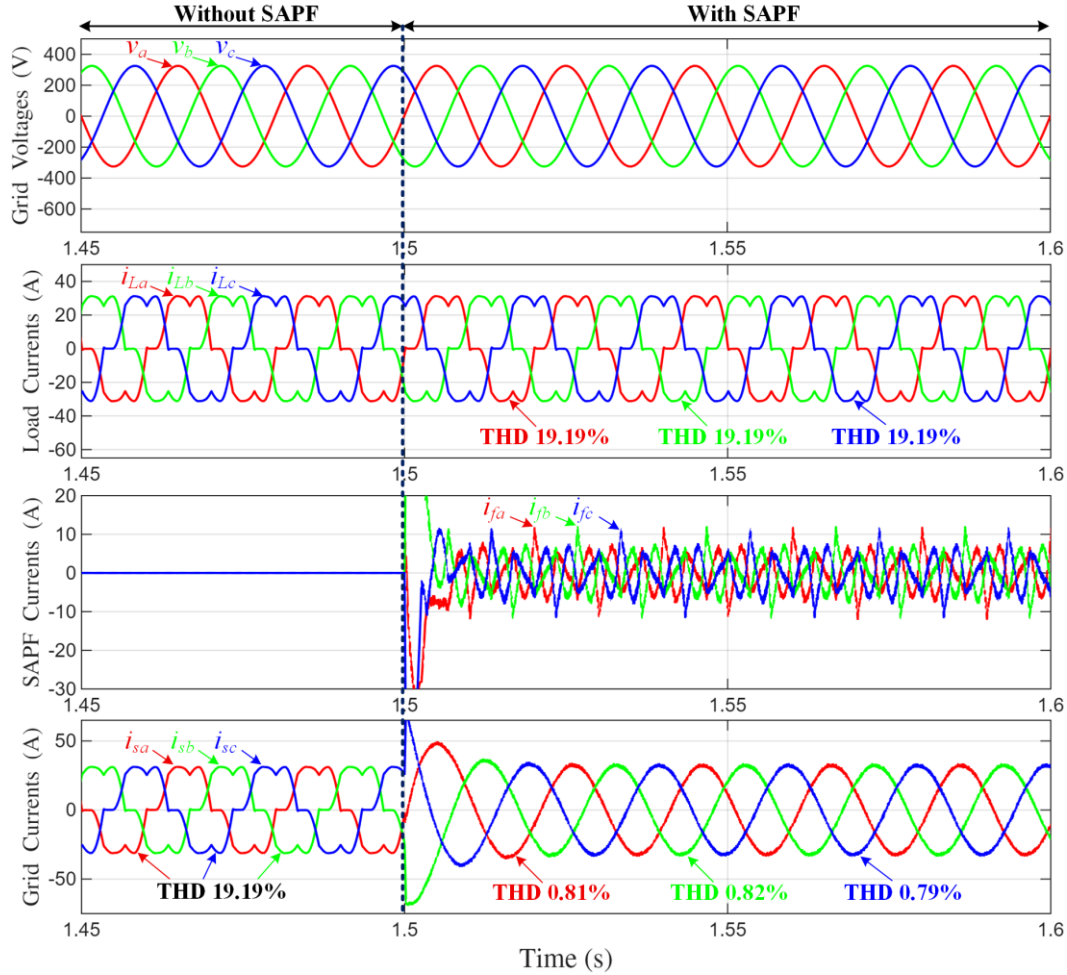


Figure 4. Grid voltages (v_a , v_b , v_c), load currents (i_{La} , i_{Lb} , i_{Lc}) SAPF compensating currents (i_{fa} , i_{fb} , i_{fc}) and grid currents (i_{sa} , i_{sb} , i_{sc}) under sinusoidal grid voltage and nonlinear load conditions.

Results and Discussion

To evaluate the performance of the DSOGI-PLL and MAF-based SAPF control method, simulation studies are carried out in the MATLAB/Simulink environment under both sinusoidal and distorted grid voltage conditions with a nonlinear load. The system is modeled using a discrete-time approach with a sampling time of $1e-5$ s. The grid voltage is set to 400 V (line-to-line) with a frequency of 50 Hz, while the interfacing inductor and DC-link capacitor are selected as 2 mH and 2500 μ F, respectively.

Fig. 4 illustrates the grid voltages v_a , v_b , v_c , the nonlinear load currents i_{La} , i_{Lb} , i_{Lc} , the compensating currents generated by the SAPF i_{fa} , i_{fb} , i_{fc} , and the source currents drawn from the grid i_{sa} , i_{sb} , i_{sc} . In addition, the figure presents a comparison between the operating conditions when the SAPF is disabled and when it is activated. First, the performance of the system is evaluated under sinusoidal grid voltage and nonlinear load conditions. When the grid voltages v_a , v_b , v_c , shown in Figure 4 are examined, it can be observed that the three phases are balanced and have a sinusoidal waveform. Due to the nonlinear load, the load currents i_{La} , i_{Lb} , i_{Lc} , contain significant harmonic components, resulting in noticeably distorted current waveforms. Under these conditions, the THD of the load currents is approximately 19.19%.

When the source currents i_{sa} , i_{sb} , i_{sc} are examined, it is observed that the harmonic components generated by the nonlinear load are directly transferred to the grid current when the SAPF is not operating. As a result, the source currents exhibit highly distorted waveforms, and the THD value reaches approximately 19.19%. When the SAPF is enabled using the proposed DSOGI-PLL and MAF-based control strategy, the filter produces compensating currents i_{sa} , i_{sb} , i_{sc} that are injected at the PCC to cancel the harmonic components of the load current. This compensation significantly improves the waveform quality of the source currents, making them

nearly sinusoidal. Consequently, the THD of the source currents decreases from 19.19% to 0.81%, 0.82%, and 0.79%, respectively. These results confirm that the proposed control approach provides effective harmonic suppression under sinusoidal grid voltage conditions.

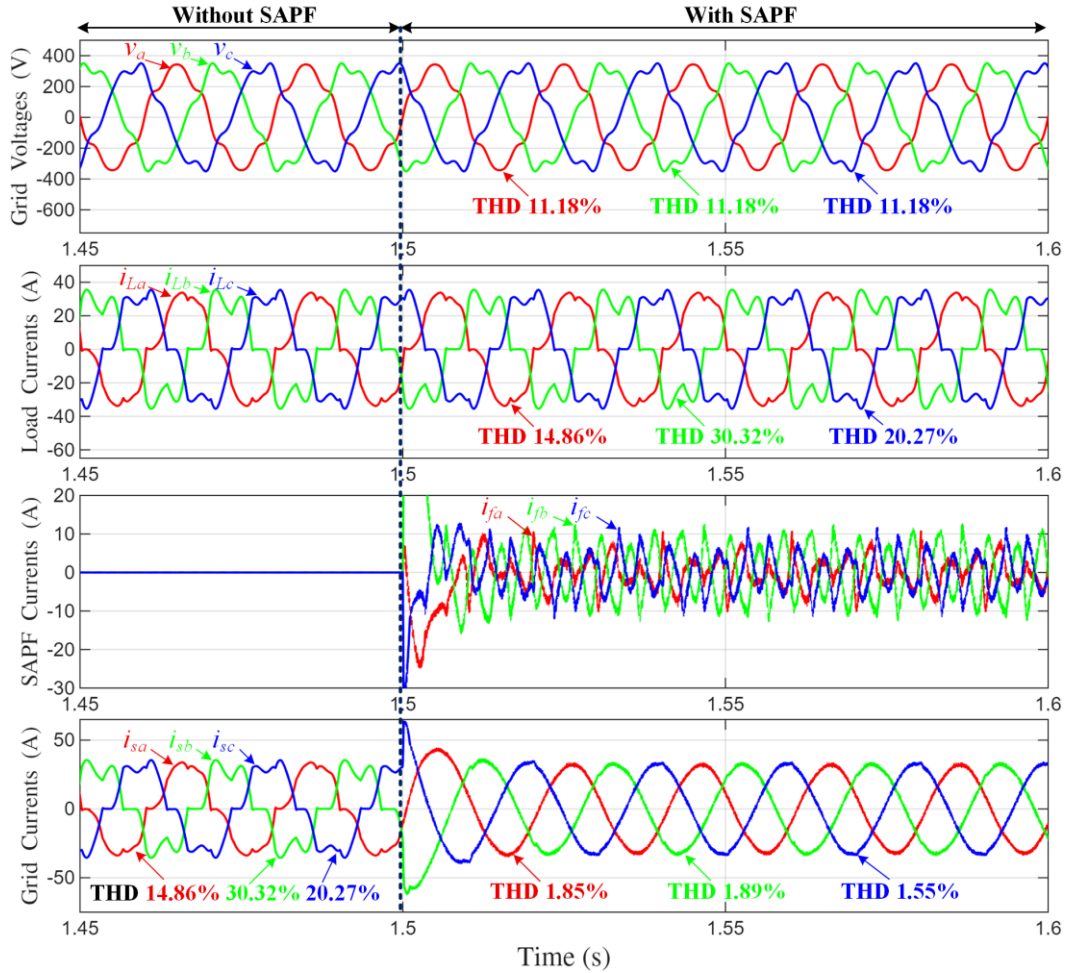


Figure 5. Grid voltages (v_a , v_b , v_c), load currents (i_{La} , i_{Lb} , i_{Lc}) SAPF compensating currents (i_{fa} , i_{fb} , i_{fc}) and grid currents (i_{sa} , i_{sb} , i_{sc}) under distorted grid voltage and nonlinear load conditions.

To further evaluate the performance of the proposed DSOGI-PLL and MAF-based SAPF control strategy under more challenging operating conditions, simulation studies are conducted for the case of distorted grid voltage and nonlinear load. Fig. 5 illustrates the grid voltages v_a , v_b , v_c , the load currents i_{La} , i_{Lb} , i_{Lc} , the compensating currents generated by the SAPF i_{fa} , i_{fb} , i_{fc} , and the source currents i_{sa} , i_{sb} , i_{sc} .

Under distorted grid voltage conditions, both the grid voltages v_a , v_b , v_c , and load currents i_{La} , i_{Lb} , i_{Lc} , contain significant harmonic components. When the SAPF is not in operation, these harmonics propagate directly to the source currents, causing considerable waveform distortion. After the activation of the SAPF with the proposed DSOGI-PLL and MAF-based control method, the filter injects appropriate compensating currents to mitigate the harmonic components present in the system. As a result, the source currents become considerably smoother and closer to sinusoidal waveforms despite the presence of grid voltage distortion. The THD values of the source currents are reduced to 1.85%, 1.89%, and 1.55%, respectively. This outcome demonstrates that the proposed control method maintains strong harmonic mitigation capability even under distorted grid voltage and nonlinear load conditions.

This outcome demonstrates that the proposed control method maintains strong harmonic mitigation capability even under distorted grid voltage and nonlinear load conditions. Overall, these results clearly demonstrate the effectiveness, robustness, and practical applicability of the proposed DSOGI-PLL and MAF-based control strategy. Furthermore, the achieved THD values satisfy the requirements of the IEEE 519-2014 standard, indicating that the proposed method provides a reliable solution for power quality improvement.

Conclusion

In this study, an improved dq -based control strategy is proposed for shunt active power filter (SAPF) applications by combining a DSOGI-PLL-based synchronization method with a moving average filter (MAF)-based harmonic extraction approach. In the proposed method, the DSOGI-PLL structure provides accurate phase angle estimation under harmonic-contaminated grid conditions, while the MAF structure enables the extraction of the fundamental current component without introducing the delay and phase shift problems commonly associated with conventional LPF and HPF filters.

The performance of the proposed control strategy is evaluated through simulation studies conducted under different operating conditions. Under sinusoidal grid voltage and nonlinear load conditions, the THD of the source current, which is approximately 19.19% when the SAPF is not in operation, is reduced to 0.79% using the proposed method. Under distorted grid voltage and nonlinear load conditions, the TDD values of the source currents are reduced to 1.85%, 1.89%, and 1.55%, respectively.

The obtained results demonstrate that the proposed DSOGI-PLL and MAF-based control strategy provides high harmonic mitigation performance under both sinusoidal and distorted grid conditions. Furthermore, the resulting TDD values remain below the limits specified in the IEEE 519-2014 standard. Therefore, the proposed method can be considered an effective solution for improving power quality in SAPF applications.

Scientific Ethics Declaration

* The author declares that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the author.

Conflict of Interest

* The author declares that there is no conflict of interest.

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Author(s) Information

Ali Sait Ozer

Department of Control and Automation
Technology, Konya Technical University,
42250, Konya, Türkiye;
ORCID iD: <https://orcid.org/0000-0002-8430-2887>
*Contact e-mail: asozer@ktun.edu.tr

*Corresponding author(s) contact email

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Optimization of 3D Printing Parameters for Compressive Strength of PLA Using the Taguchi Method

Ahmet Saygin Ogulmus
OSTIM Technical University

Yusuf Sahin
OSTIM Technical University

Mehmet Sahbaz
Karamanoglu Mehmetbey University

Fatih Baykal
OSTIM Technical University

Abstract: Fused Deposition Modeling (FDM) has significantly advanced in the additive manufacturing of complex geometrical and customized parts, particularly for thermoplastics like Polylactic Acid (PLA). The purpose of the present study is to optimize FDM process parameters to improve the compressive strength of 3D-printed PLA using the Taguchi method. Four process parameters such as infill density, printing speed, layer thickness, and infill pattern type are selected. Among these parameters applied, printing speed had a significant impact on compressive strength. Analysis of variance results revealed that printing speed was dominant, followed by layer thickness in analyzing the compressive strength, but the infill density and infill pattern were not significant. Confirmation tests were provided by Taguchi method. Further, it is found that the optimal compressive strength was achieved with a printing speed of 300 mm/s, a layer thickness 0.3 mm, an infill density of 10, and a pattern shape of grid. Therefore, trial 3 yielded the highest compressive strength results at approximately 42.45 MPa, which is slightly higher than those reported in prior studies.

Keywords: An additive manufacturing, Fused deposition modelling, Polylactic acid, Compressive strength, Taguchi method, Optimization

Introduction

Any type of products in additive manufacturing technique (3D printing) are given design flexibility, very precise dimension on components associated with complex geometries, which are quite hard to achieve using classical production methods (Abdallah et al., 2023). Due to having design flexibility prototyping and cost advantage, 3D printing approach has moved to various industries such as automotive, aerospace, medical and sports (Arifin et al., 2021). However, this process has some dis-advantages like irregular surface, poor mechanical property and indicating low accuracy. In order to produce good quality of mechanical parts, it is necessary to produce those parts with optimum combination of process parameters.

There are several various types of additive manufacturing techniques like Fused Deposition Modelling (FDM), Fused Filament Fabrication (FFF), Stereolithography (SLA), and Selective Laser Sintering (SLS). Each one has specific advantages, depending on the application (Kumaresan et al., 2023; Hikmat et al., 2021). Polylactic Acid (PLA) is a bio-plastic commonly used in FDM 3D printing, notable for its biodegradability and environmental friendliness. Its availability is significantly supported by its excellent processability and biocompatibility. PLA

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has higher tensile strength, low warp, and low ductility when compared to ABS (Kafle et al., 2021; Solomon et al., 2021). The fused deposition modeling (FDM) is an additive manufacturing (AM) process that is often used to fabricate geometrically complex shaped prototypes and parts. The many fundamental process parameters such as nozzle diameter/temperature, fill density/fill pattern, layer thickness/height, print speed and various patterns directly affect the quality of the manufactured parts and mechanical performance (Dey & Yodo, 2019). To avoid trial and error approach on experimental work on polymeric materials, Taguchi optimization is adopted in a more systematic way and efficiently, by testing the different printing parameters because of simple, easier/less cost in short period of time.

A large number of researchers analyzed different parameters to achieve desirable properties of parts (Hema et al., 2022; Myers et al., 2022; Özmen et al., 2023; Adanur et al., 2024; Oviedo et al., 2020; Evlen et al., 2019; Kadhum et al., 2023; Ramirez-Revilla et al., 2022; Abifarin et al., 2022; Kumar et al., 2023; Khalifah et al., 2025; John et al., 2023; Singh et al., 2022), and many other researchers have worked on optimizing process parameters using DoE (Sahoo et al., 2023; Gebrehiwot & Espinosa-Leal, 2022; Alviar & Basilia, 2024; Lokesh et al., 2022; Chinchankar et al., 2024; Cui et al., 2024; Makwana, 2023; Patel et al., 2023). Hema et al. (2022) studied the effects of machine process parameters on the compressive and flexural strength of Polylactic Acid (PLA) material produced using FDM 3D printing by Taguchi design. For compressive strength, the optimal parameters were 100 μm layer height, 80% infill density and 80 mm/s printing speed. It was indicated that layer height was the most significant parameter for flexural strength (68.42% contribution), while infill density was the most significant parameter for compressive strength (62.18% contribution). Myers et al. (2022) aimed to analyze and optimize FDM additive manufacturing process parameters for cellular structures used in orthopedic scaffolds. The studied parameters included layer height (0.12, 0.16, 0.2 mm), flow rate (90%, 100%, 110%) and printing speed (40, 50, 60 mm/s). The best combination for geometric accuracy and time/cost optimization was 0.16 mm layer height, 50 mm/s printing speed, and 90% flow rate.

Özmen et al. (2023) examined the effect of infill pattern and orientation on the tensile strength of test specimens fabricated using FDM 3D printing and PLA. The different infill patterns and three infill angles (0° , 45° , 90°) were printed. Those with concentric 90° and zigzag 90° infill exhibited the highest tensile strength. The specific strength of the 30% infill concentric pattern sample was about 25% higher than that of the 100% infill sample. Adanur et al. (2024) investigated the effects of different infill patterns and angles on production time, weight and tensile and compressive strength of PLA samples. Results showed that 15% infill samples required four times less material and printing time than fully solid ones. The highest tensile strength occurred at a 45° printing angle. Among 15% infill samples, the Aligned Linear (B-0) pattern with a 0° angle had the highest strength. Oviedo et al. (2020) focused on the mechanical performance of commercial filaments based on ABS, PLA, and PLA/PHA and their corresponding 3D printed samples. Evlen et al. (2019) studied experimentally to determine the effect of infill ratio on the mechanical properties of PLA and PET materials. In PLA, tensile strength increased up to a 30% infill ratio (maximum 48 N/mm²) but then declined at higher ratios (40–50%) due to notch effects and poor layer adhesion.

Kadhum et al. (2023) searched a comprehensive study assessing the effects of fourteen different infill patterns on the mechanical and surface characteristics of 3D-printed parts. PLA+ showed the highest average strength (14.7 MPa). Ramirez-Revilla et al. (2022) evaluated the compressive and tensile properties of FDM 3D-printed polymers exposed to saline solution. In compression, PLA and PC exhibited the highest compressive strength. After degradation, the tensile strength of PLA decreased most significantly (33.55% reduction). Abifarin et al. (2022) investigated the effects and optimization of manufacturing parameters on the tensile, compressive and flexural strength of 3D-printed Chitosan/PLA scaffolds by the Taguchi-Grey Relational Analysis methodology. The optimal parameters were obtained at 1% Chitosan, 100% infill density and 70°C annealing temperature. Kumar et al. (2023) investigated the effects of different concentrations of poly(ethylene glycol) (PEG) on the properties of PLA parts. The PLA/PEG blend containing 5% PEG showed optimal structural and mechanical properties.

Khalifah et al. (2025) studied that the Taguchi method/Analysis of Variance are selected in optimizing the fused filament fabrication process to produce PLA composites. The tensile strength increased to 40 MPa instead of 35 MPa. Among the parameters, only nozzle temperature and infill density had a significant impact on tensile strength. John et al. (2023) studied the influence of nozzle diameter, strain rate, and geometric patterns on the mechanical properties of PLA samples. Singh et al. (2022) applied a Taguchi-based DoE to optimize the layer height and infill pattern for PLA surgical equipment produced via FFF. They obtained a tensile strength of 42.6 MPa and an elasticity modulus of 32.74 MPa.

The literature surveys indicate that there are many studies carried out to optimize the mechanical properties of PLA/PEG/ASA through various methods, most of them concentrated on the effect of process parameters on tensile

strength, and limited number of studies related to compressive property of PLA materials (Hema et al., 2022; Adanur et al., 2024; Ramírez-Revilla et al., 2022; Abifarin et al., 2022). The purpose of this study is to determine and optimize the process parameters infill density, printing speed, layer thickness and infill pattern on PLAs using the Taguchi method. Each parameter's effect on process performance will be searched in terms of the Taguchi L9 design due to becoming more systematic, saving time and costly. Experiments are made for validation to confirm the results of optimization.

Method

Taguchi Method

In this case, an orthogonal array like L9 (3^4), as indicated in Table 3, is quite applicable for 9 experimental trials with four factors at three levels each. This array provides a symmetrical and comprehensive assessment of the main effects while minimizing confounding, meaning that the effects of two or more factors cannot be distinguished. The use of the L9 array ensures that the effects of any factors are unbiased during estimation, allowing accurate and reliable conclusions to be drawn through this approach.

This technique is employed to determine the optimal machining parameters. The Signal-to-Noise Ratio (SNR) is utilized to evaluate the robustness of the process and analyze the system's response under varying conditions. There are three common types of SNR formulations: **Smaller-is-Better (SB)**, **Larger-is-Better (LB)** and **Nominal-is-Best (NB)**. In this study, **compressive strength (CS)** is considered a response to be maximized. Therefore, the LB characteristic is applied for CS using Eq. (1).

If LB is effective, Eq. (1) is used.

$$SNR (dB) = -10 \log \left(\frac{1}{n} \right) \sum_{i=1}^n \left(\frac{1}{y_{ij}^2} \right) \quad (1)$$

Where, n shows the number of replicates while Y_{ij} exhibits the outputs. Highest SNR will give an optimal solution.

Materials

PLA was the filament used to prepare the compressive specimens. Commercially available from Filament Company of 1.75 mm diameter (Shenzhen, China), some technical specifications of composite PLA are given in Table 1. Compressive test samples were produced using the Flashforger Guider IIs FFF technology-based 3D printer, in Beijing, China and modeled using CAD software with Solidworks 2020. Once the model is sliced through the Flashprint slicing software, G-code is generated. It is a set of commands telling a 3D printer how to print objects. Examples of information that G-code conveys are how the printer moves, at what speed, and the required temperature of the extruder. Sliced code is a code comprising directives along with both variables and constant parameters necessary for the slicing program. Table 1 presents some physical and mechanical properties of PLA filament, including tensile strength, elongation at break, density, melting temperature and glass transition temperature.

Table 1. Properties of Polylactic Acid (PLA) filament Property.

	Value	Units
Density	1.24	Kg / m ³
Elongation at break	6.3	%
Ultimate tensile strength	52.9	MPa
Tensile modulus	1146	MPa
Rockwell hardness	80	Hr
Melting temperature (T _m)	185	C°
Glass transition temperature	62	C°

The variable parameters set for the 3D printing process through FlashPrint software in the case of PLA are noted in Table 2 that are infill density (A), printing speed (B), layer thickness (C) and infill pattern (D), respectively.

Table 2. Variable parameters used in Flashprint software.

No	Process parameters	Levels			Units
		1	2	3	
1	Infill Density (A)	10	30	50	%
2	Printing Speed (B)	100	200	300	mm / s
3	Layer Thickness (C)	0.11	0.2	0.3	mm
4	Infill Pattern (D)	Honeycomb	Zigzag	Grid	-

The following Taguchi L9 orthogonal array (Table 2) was used for the design of the experiment, showing various combinations of the four process parameters: infill density, printing speed, layer thickness and infill pattern. This will systematically allow the study of multiple factors affecting the comprehensive strength of 3D-printed PLA.

Results and Discussion

Optimization of Process Parameters

The term noise factor actually designates a controllable variable analogous to levels of temperature and humidity in ambient air. The results of the compressive strength testing in Table 3 showed that process parameters such as printing speed and layer thickness had a significant impact on the mechanical properties of 3D-printed PLA. The printing speed was the single most influential factor that accounted for a 35.79% variation in compressive strength that improved internal bonding and structural integrity as its speed increased. Further improvement of compressive properties is attained through the establishment of the layer thickness at about 27.61%. The infill density and pattern type had less effective but still important roles in optimizing process and minimizing thermal degradation. These results are also given that the optimized parameter achieved a maximum compressive strength of 42.45 MPa, well above the normal tensile strength of standard PLA, which ranges from 30 to 35 MPa. This indicates the effectiveness of parameter optimization in improving the mechanical performance of 3D printing fabricated PLA products.

Table 3. Results of compressive strength testing and signal-to-noise (S/N) ratio analysis for 3D printed PLA specimens

Basic factors applied in testing the compressive test					Mechanical properties (MPa)	
	Infill Density (%), A	Printing (mm/s), B	Speed	Layer Thickness (mm), C	Pattern Type, D	PLA- Force, N PLA,YS-2%
1	10	100		0.1	Honeycomb	2180.39
2	10	200		0.2	Zigzag	2951
3	10	300		0.3	Grid	5412.24
4	30	100		0.2	Grid	1933.42
5	30	200		0.3	Honeycomb	2510.25
6	30	300		0.1	Zigzag	2735.58
7	50	100		0.3	Zigzag	2758.34
8	50	200		0.1	Grid	3046.12
9	50	300		0.2	Honeycomb	3082.09

Figure 2 further illustrates the graph of the mean effects plot of compressive test response or performance evaluations of materials in terms of SNR under given processing conditions. Based on the data presented in this figure and table 3, printing speed is the most influential parameter, changed more or less linearly with speed, followed by layer thickness and pattern. Both infill density and pattern firstly decreased up to medium point after that it started to increase linearly again. Further, our experimental results indicated that the optimum testing parameters are provided at the third trial of experiment because of using the A1, B3, C3, D3 level when tested compressive testing. In other words, the optimum condition can be obtained at infill density of 10, printing speed of 300 mm/s, layer thickness of 0.3 mm, and pattern type of grid.

Table 4 exhibits the results of compressive testing Response Table for SNR. It is indicated that factor B is the most significant factor affecting the SNR because it holds the topmost (rank 1), followed by layer thickness (rank 2), infill density (rank 2), infill pattern holds the least effect (rank 4).

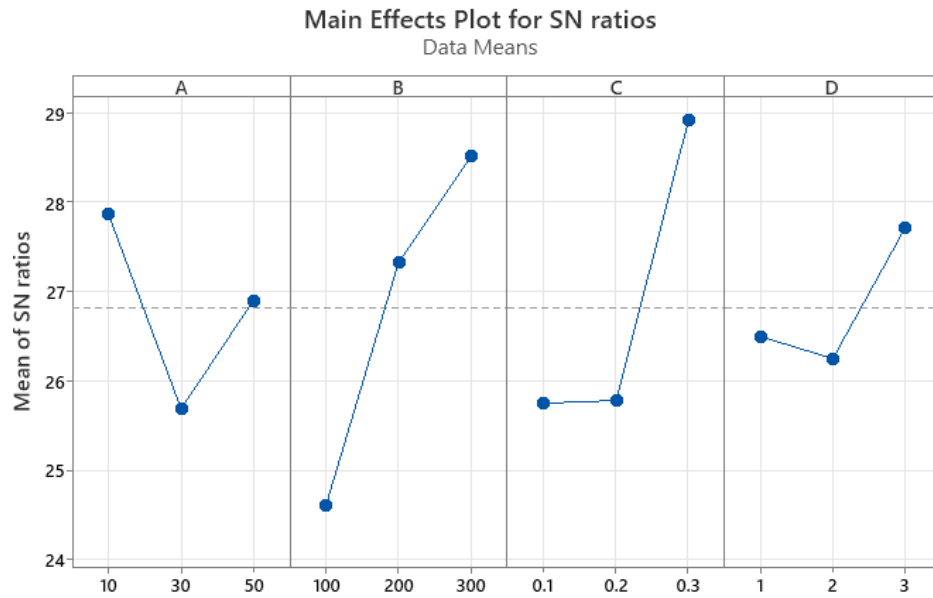


Figure 2. Main effect plot for SN ratio using Minitab software for six parameters.

Table 4. Response table for S/N ratio

Levels	Infill density (A)	Printing Speed (B)	Layer thickness (C)	Infill pattern (D)
1	27.86	24.60	25.75	26.49
2	25.68	27.32	25.78	26.25
3	26.90	28.51	28.92	27.71
Delta (Δ)	2.18	3.91	3.17	1.46
Ranking	3	1	2	4

Analysis of Variance (ANOVA)

ANOVA is a computational method used to assess error variance and determine effect of process parameters on performance characteristics like compressive strength. Table 5 indicates the ANOVA analysis performed and the results are given here. The Fisher's ratio (F-value) is employed in the ANOVA. The calculated F-test is smaller than the critical F-table at $\alpha=0.05$, derived from the null hypothesis i.e. $F_{0.05,1,4} = 7.71$, there is a no statistically significant relationship between the input factors and outputs. Among the four factors together in the model, infill density, printing speed, layer thickness, and pattern other factors were not found an effective because their p-values are 0.343, 0.064, 0.089, 0.296, respectively, which are higher than 0.05 value. Additionally, the contribution (%) is mostly comes from the factor B (35.79%), followed by factor C (27.61%), factor D (7.97%) and finally factor A (6.39%), respectively, when tested at compressive testing. Again, the layer thickness was the second most influential factor noted, accounting for 27.61% variation in compressive strength measurement. This means that while the choice of layer thickness becomes influenced, it is lesser than that of printing speed; it still remains a considerable force when considering an improvement in the mechanical integrity of printed material. On the other hand, the pattern had a small effect on compressive strength; therefore, pattern changes do not affect the strength properties of the material.

Table 5. Analysis of variance of the compressive strength of PLA

Source	DF	Adj SS	Contribution(%)	Adj MS	F-Value	F-table	P-Value
Regression	4	402.67	77.849	100.67	3.51		0.125
A	1	33.08	6.39	33.08	1.16		0.343
B	1	185.51	35.79	185.51	6.48	7.71	0.064
C	1	142.81	27.61	142.81	4.99		0.089
D	1	41.26	7.97	41.26	1.44		0.296
Error	4	114.57	22.15	28.64			
Total	8	517.24	100				

Figure 3 illustrates a Normal Probability Plot for a dataset for PLA samples. This data does not follow a normal distribution. P-value obtained is 0.019: In statistical analysis, we typically use an alpha level of 0.05. Since 0.019 value is less than 0.05, the hypothesis is rejected that the data is normal. In graph, AD (Anderson-Darling) shows the 0.828. This is a "goodness of fit" test. For a sample size this small (N=9), an AD value this high generally indicates a poor fit for the normal distribution. The single blue point far to the right (at approximately 43) can be outlier. The rest of the data is clustered between 15 and 25. This one "heavy" data point is pulling the mean up and is the primary reason the P-value is so low. If the data were perfectly normal, the blue dots would form a tight, straight line along the center red line. Instead, they follow an "S" shape, which suggests the distribution has skewness or heavy tails. While most points stay within the curved red lines (the 95% Confidence Interval), they are drifting toward the boundaries, particularly at the high end.

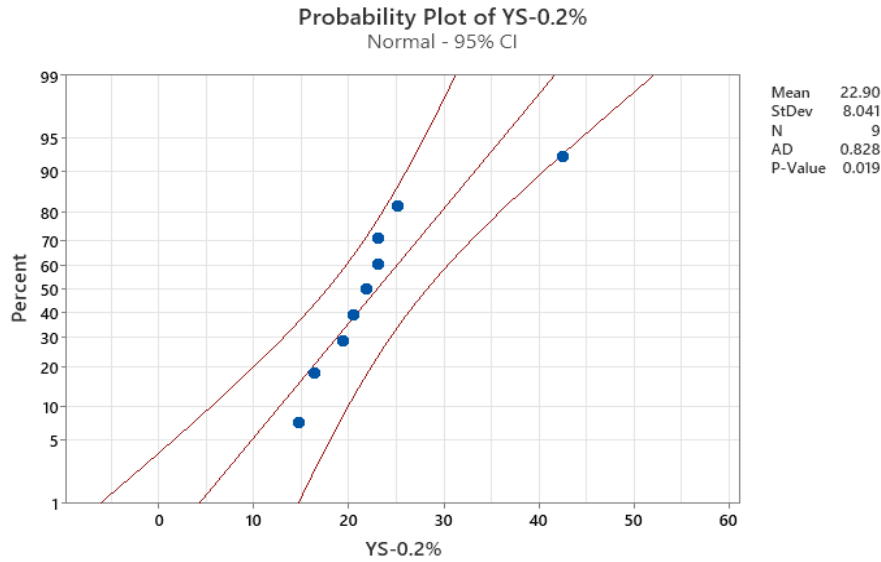


Figure 3. Normal probability plot.

Optimum Cutting Conditions

The optimal testing conditions for improved compressive strength can be obtained from main effects plot for mean data in terms of SNR, as shown in Fig. 2. The optimal values for the parameters were A1=10, B3 = 300 mm/s, D3 = 0.3 mm, and D3 = 3 (grid), as exhibited in the following response, as shown in Table 6.

Table 6. Optimum conditions for CS.

Parameter	Notation	Best level	Value
Infill density	A	1	10
Printing speed	B	3	300
Layer thickness	C	3	0.3
Fill pattern	D	3	3

Estimation of Optimum CS/Confirmation Tests

In the final step, it is necessary to perform a verification experiment in order to validate the precision of the optimization. The experiment was conducted using the optimal levels of the variables that were selected, as presented in Table 7 with two repeated tests. It is determined to be (A1-B3-C3-D3), as can be given in Eq. (3).

$$CS_{opt} = Y_m + (A_1 - Y_m) + (B_3 - Y_m) + (C_3 - Y_m) + (D_3 - Y_m) \quad (3)$$

where the variable Y_m represents the mean value of performance attributes for CS, as indicated by all L9 measurements in Table 7. The CS_{opt} denotes the anticipated average of the CS when subjected to ideal conditions. Based on the model, the optimal testing performance for CS is obtained at a first level of infill density, 3rd level of printing speed, 3rd level of layer thickness and 3rd level of pattern type as well. The response averages are computed and the resulting values are presented below. The CR values for Y_m , A1, B3, C3 and D3 are 26.814

dB, 27.86 dB, 28.51 dB, 28.92 dB and 27.71 dB, respectively, and their corresponding values are 34.96, 10, 300, 0.3 and 3, respectively. Upon incorporation of the aforementioned values into Eq. (2), it is projected that the optimal magnitude of CS will manifest as 30.92 dB. It is reported that statistical analysis can only be deemed reliable if the error values remain below 20%.

Table 7. Confirmation test results.

Level	Taguchi method based on (Eq. 2)		
	Exper.	Predict.	Error (%)
A1B3C3D3 (Optimum)	34.03	32.558	4.44
A3B2C3D2 (Random)	28.5	25.81	10.42

Our results can be compared to more recent research works conducted at the tensile/compressive strengths of PLAs. For example, the research results of Lokesh et al. (2022), who recorded a 30 to 40 MPa confidence interval. Similar results were reported by John et al. (2023), Patel et al. (2023) provided confidence limits of 35 to 45 MPa, related to the effect of production processes on the tensile strength. The higher performance can be attributed to differences in sample preparation and printing techniques, various parameters and equipment. There were no full agreement on mechanical properties of polymeric materials among the previous studies. Some researchers indicated that infill density was the most significant parameter for compressive strength of PLAs (Özmen et al., 2023; Evlen et al., 2019; Abifarín et al., 2022), infill angle (Adanur et al., 2024), layer height (Hema et al., 2022) while others only nozzle temperature and infill density (Khalifah et al., 2025) and nozzle diameter (John et al., 2023) had a significant impact on tensile/compressive property of polymeric samples. Whereas, Singh et al. (2022) revealed that the layer height and infill pattern for PLA surgical equipment. Such variations in experimental study exhibited the need for process optimization with respect to material performance enhancement. It can be suggested that this approach can serve as a benchmark for future studies in this area.

Conclusion

The fused filament fabrication process is adopted to produce PLA materials under different conditions and is optimized through the Taguchi method and Analysis of Variance (ANOVA). Analysis of variance results indicated that printing speed was the first effective parameter, followed by layer thickness in analyzing the compressive strength, but the infill density and infill pattern were not significant. The experimental results revealed that the optimal compressive strength was achieved with a printing speed of 300 mm/s, a layer thickness of 0.3 mm, infill density of 10 and a pattern of grid. Furthermore, trial 3 yielded the largest strength results at approximately 42.45 MPa, which is higher than those reported in prior studies. Future works should be considered in examining additional parametric variations as well as different materials like PETG and ASA, and apply to multi-objective approach to further validate and refine the finding results here.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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Author(s) Information

Ahmet Saygın Ogulmus

Department of Industrial Design,
OSTIM Technical University, Ankara, Türkiye
ORCID iD: <https://orcid.org/0000-0001-6498-4318>
*Contact email: ahmet.saygin@ostimteknik.edu.tr

Yusuf Sahin

Department of Mechanical Engineering,
OSTIM Technical University, Ankara, Türkiye
ORCID iD: <https://orcid.org/0009-0003-9311-0865>

Mehmet Sahbaz

Department of Mechanical Engineering,
Karamanoglu Mehmetbey University Karaman, Türkiye
ORCID iD: <https://orcid.org/0000-0001-6379-8345>

Fatih Baykal

Department of UAV Technology and Operator,
OSTIM Technical University, Ankara, Türkiye
ORCID iD: <https://orcid.org/0000-0002-2842-584X>

*Corresponding author(s) contact email

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Numerical Analysis and Optimization of Hydroforming Parameters of a 2024-T3 Aluminum Alloy Interface Part for Aerospace Applications

Caner Ture

Konya Technical University

Batuhan Katirci

Konya Technical University

Mevlüt Turkoz

Konya Technical University

Abstract: This study investigates the production of a 2024-T3 aluminum alloy interface component, designed for the mounting of a commercial antenna onto a helicopter tail, using the hydroforming process. Hydroforming is a widely utilized sheet metal forming technique in aerospace applications, operating on the principle of utilizing high fluid pressure to induce plastic deformation of the blank into a male or female die. Compared to conventional forming methods, it enables the production of complex geometries with superior quality. Within the scope of this work, the interface part was first designed to conform to the surfaces of both the antenna and the helicopter tail, followed by the development of the female hydroforming die geometry. The effects of critical process parameters, such as fluid pressure, blank holder force (BHF), and initial blank dimensions, on thinning and stress distribution were examined through Finite Element Analysis (FEA) based on the Forming Limit Diagram (FLD) and material hardening criteria. Through iterative simulations, the optimal process parameters required to prevent potential failure modes, such as tearing and wrinkling, were identified. The results indicate that fluid pressures reaching 50 MPa are necessary for successful forming, with a minimum achievable corner radius of 22 mm. Consequently, it is demonstrated that 2024-T3 alloy can be effectively formed into complex aerospace components using the hydroforming method.

Keywords: Interface, Hydroforming, Die, Press, Sheet metal

Introduction

In the literature, the hydroforming (hydraulic forming) process, also referred to as fluid forming, flexible die forming, or rubber diaphragm forming, is defined as the forming of sheet or tubular metallic materials in a closed container by means of a fluid medium (water, viscous fluid, polymeric material, etc.) that acts as a male or female die. Due to the incompressible nature of the fluid, materials are formed by the effect of the pressure generated during the forming process (Altan, 2006; Singh, 2003; Zhang et al., 2004). This method, which first emerged in the 1890s with initial research conducted in the aerospace sector in Germany and in various fields in Japan, did not receive sufficient attention until the 1990s due to certain technical difficulties. Today, however, thanks to advancements in computer control and hydraulic systems (Karaağaç & Özdemir, 2011; Koç & Cora, 2008), its use is rapidly increasing, particularly in the automotive industry (Karaağaç & Özdemir, 2013; Kılıç & Öztürk, 2016; Özek & Taşdemir, 2017). In the hydroforming process, which provides many advantages over conventional forming and welded joining methods, sheets of different thicknesses can be formed with a single die; precise die matching is not required, and dies can be manufactured using lower-grade materials. Consequently, tooling costs are reduced by up to 90%. Furthermore, because the fluid applies a uniformly distributed load across the entire surface of the sheet and reduces friction between the sheet metal and the die, thereby decreasing local stress

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concentrations (tensile force), thinning in the sheet metal is minimized, and a uniform thickness distribution is achieved (Kandil, 2003; Zhang, 1999; Zhang & Danckert, 1998). As a result of these effects, difficult-to-form and complex parts can be produced at a lower cost, in fewer stages, and with higher strength and dimensional accuracy (Ankaralı et al., 2020; Zhang et al., 2004).

In female die sheet hydroforming (Figure 1), which is a type of the hydroforming process, only a female die is present, and the high-pressure fluid acts as the punch (Önder & Tekkaya, 2008). In this method, after the sheet material is placed on the die and the blank holder is closed, fluid pressure is applied through an integrated channel. To prevent fluid leakage during forming, the blank holder force must be regulated against the applied pressure (Groche & Metz, 2006). From an engineering perspective, the Finite Element Method (FEM) is widely used to verify the functionality of the product and the suitability of the production process prior to actual manufacturing (Şanay, 2010). A review of the literature reveals that while there are numerous studies conducted with male dies (Khandeparkar & Liewald, 2008; Palumbo et al., 2004a; Qin & Balendra, 2004; Wu et al., 2004), studies related to female dies remain relatively limited. Palumbo et al. (2004a, 2004b) performed FEM simulations on the production of complex (cylindrical, square, and compound) geometries using a female die and investigated the failure zones at the corner radii. Kleiner et al. (2004) stated that this method provides high shape and dimensional accuracy; however, they revealed that the friction generated between the sheet and the die with increasing pressure creates a disadvantage in the forming of deep parts.

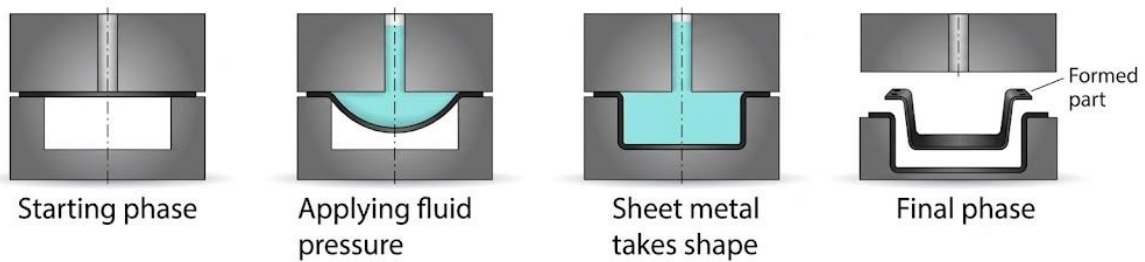


Figure 1. Stages of the hydroforming process.

In the hydromechanical forming method, numerous developments have been made in the literature to increase formability (the limiting drawing ratio). Lang et al. (2009), Verma & Chandra (2006), and Hatipoğlu (2007) demonstrated that by applying pre-bulging pressure, the material's resistance to tearing can be increased through strain hardening. Kandil (2003), Dachang et al. (2005), Abedrabbo et al. (2007), Lang et al. (2004), and Khandeparkar & Liewald (2008) conducted various studies on determining the optimum parameters for a successful forming process; while Zhang et al. (2003) and Lang et al. (2004) analyzed the effects of these parameters through numerical simulations. Using fluid pressure instead of a blank holder to reduce friction (Shirizly et al., 1994; Tirosh et al., 1996; Zhang & Danckert, 1998), hydrodynamic deep drawing which allows high-speed fluid flow (Hsu & Hsieh, 1996; Pennington, 1996), the use of radial fluid pressure (Lang et al., 2004; Yang et al., 1995), active material flow control via drawbeads (Siegert et al., 2000), and the use of viscous fluid (Liu et al., 2000) are other prominent innovative approaches.

While adjusting a male die is a demanding process, forming with a female die can be controlled with fixed parameters and simpler hydraulic systems. However, in this method as well, as the sheet material comes into contact with the female die, friction increases, and localized thinning occurs. In this study, it is aimed to produce sheet metal products, which are conventionally manufactured in multiple stages by deep drawing, in fewer stages, rapidly, and economically. For this purpose, the design and manufacturing of hydroforming dies were carried out to minimize the friction between the sheet and the die and to achieve a much more uniform thickness distribution in the part by making the entire die movable in the female die sheet hydroforming process.

Materials and Methods

For the interface design, SolidWorks 2021 was utilized during the design phase, while the commercial software LS-DYNA was employed for the analysis phase. The interface was designed for the Ga-58 commercial antenna, whose technical drawing is presented in Figure 2. The antenna was modeled in a CAD environment. Subsequently, the interface design phase was carried out in accordance with its base dimensions.

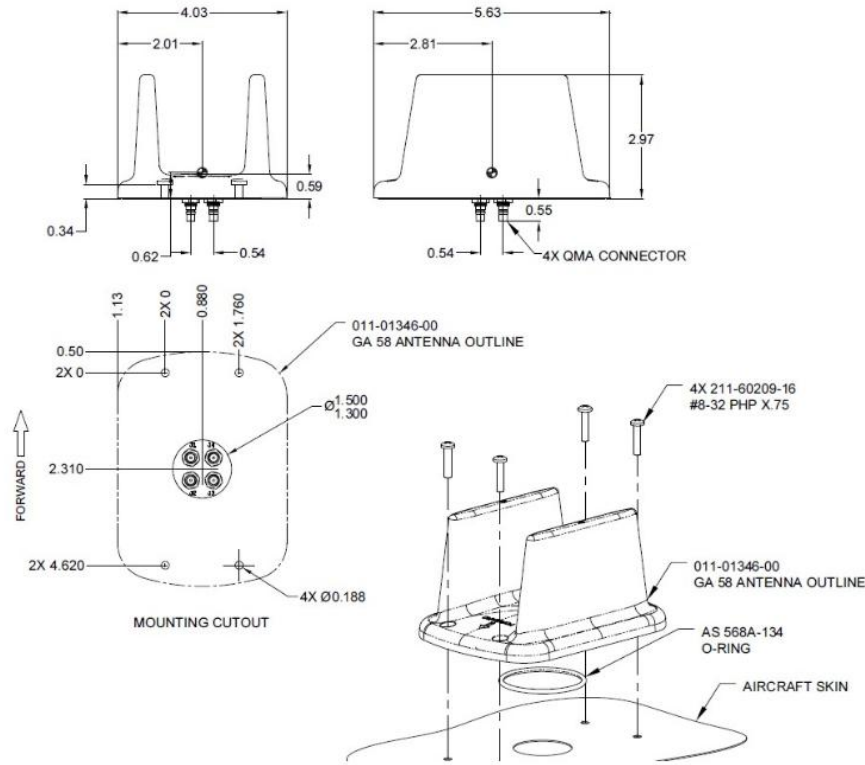


Figure 2. Technical drawing of the Ga-58 commercial antenna (Faders, 2018).

In the interface design, mounting on a helicopter tail with a diameter of 1000 mm and an inclination of 10 degrees was taken into consideration. The part, designed with a thickness of 1 mm, is fastened to the antenna using bolts. The mounting on the tail side, on the other hand, will be carried out using 3.2 mm rivets. In accordance with generally accepted manufacturing rules, the arrangement was configured such that the rivet edge distance is $2D+1$, the distance to the radius is $D+1$, and the distance between two rivets (rivet pitch) is between $4D$ and $6D$, where D is the rivet diameter. The general dimensions of the designed interface part are presented in Figure 3.

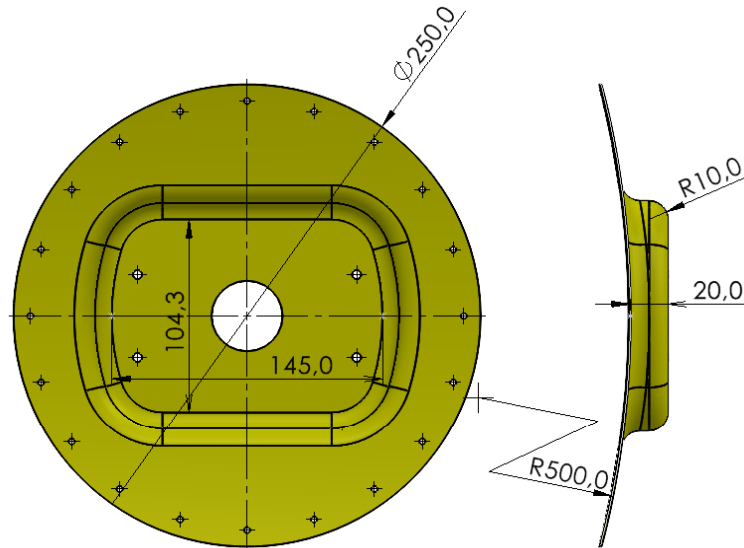


Figure 3. Technical drawing of the designed interface part.

Following the design of the interface part, the die and blank holder required to achieve its geometry were designed. In order to obtain the flange geometry of the part, which will fit onto the helicopter fuselage, by forming it between the die and the blank holder, the die geometries were determined in accordance with the flange geometry (Figure 4).

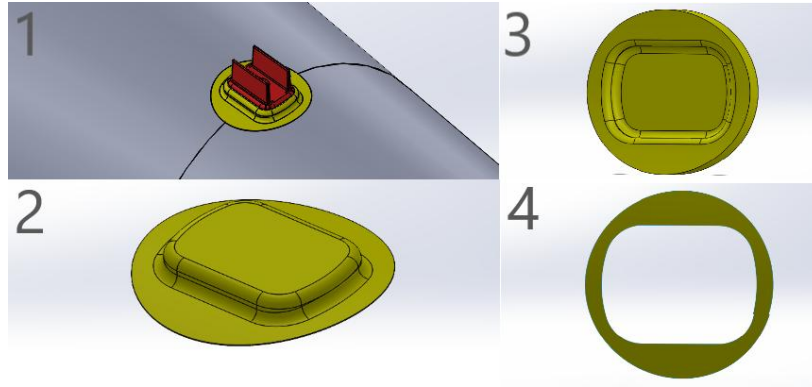


Figure 4. Die, blank holder, and interface designs.

2024-T3 was selected as the material for the interface part. Some mechanical properties of 2024-T3 are presented in Table 1.

Table 1. Mechanical properties of 2024-T3 (ASM Material Data, n.d.)

Yield Strength	345 MPa
Tensile Strength	483 MPa
Density	2.78g/cm ³
Modulus of Elasticity	73.1 GPa
Poisson's Ratio	0.33
Strain Hardening Exponent	0.16
Strength Coefficient	690 MPa

The strain hardening exponent and strength coefficient are material properties used in cold forming methods. They are derived to describe the plastic flow region of the stress-strain curve. This derived expression is called the “Hollomon Equation”. The strain hardening exponent represents a material's capability to strain harden. Its high values indicate that the material has a ductile structure and is capable of strain hardening. The strength coefficient, on the other hand, provides information about the hardness of the material. It determines the material's resistance to plastic deformation.

Following the design phase, forming analyses were conducted using the LS-DYNA software. Initially, the geometries of the die, blank holder, and sheet metal part were prepared for analysis. While keeping the material thickness and hydraulic pressure values constant, the effects of blank holder forces of 20, 30, 40, 80, 120, and 160 kN, along with coefficient of friction parameters of 0.05, 0.1, and 0.17 established within the program, on the thinning of the sheet were investigated.

Results and Discussion

When the analyses conducted in the FEA model, which was established for the hydroforming of the interface part designed to ensure the integration of the Ga-58 commercial antenna into the helicopter tail, were executed, the pressure values at which the sheet metal part took the shape of the die and the resulting percentage thinning amounts in the sheet are presented in Table 2. The variation in percentage thinning with blank holder force at different coefficients of friction is given in Figure 5.

The maximum thinning in the part occurs at the bottom corners, as shown in Figure 6. As can be understood from Figure 5, the most significant factor affecting the thinning of the part is the coefficient of friction. As the coefficient of friction increases (from 0.05 to 0.17), the flow of the sheet metal into the die becomes more difficult, and the material is forced to stretch. At a friction of 0.05, the thinning rates remain at a relatively low level (13.1%–14.8%). At a friction of 0.10, the thinning rates began to increase and were observed between 15.9% and 18.5%. The high friction at 0.17 caused excessive straining of the material, and the thinning rates rose up to 30%, increasing the risk of tearing to the maximum level. The increase in the blank holder force creates a holding effect that restricts the flow of the material in the flange region into the die. Especially in cases where friction is high (0.17), increasing the blank holder force from 20 kN to 160 kN significantly increased the thinning from 19.6% to 30.1%. In cases where friction is low (0.05), the increase in blank holder force had a relatively smaller effect on thinning.

Table 2. Analysis results

No	Blank Holder Force (kN)	Coefficient of Friction	Pressure (MPa)	Thickness (mm)	Thinning (%)
1-	20	0.05	57.14	0.868	13.182
2-	30	0.05	57.14	0.866	13.359
3-	40	0.05	60.71	0.851	14.863
4-	80	0.05	60.71	0.858	14.116
5-	120	0.05	60.71	0.855	14.491
6-	160	0.05	57.14	0.856	14.372
7-	20	0.1	60.71	0.840	15.995
8-	30	0.1	60.71	0.829	17.086
9-	40	0.1	60.71	0.872	17.275
10-	80	0.1	60.71	0.826	17.341
11-	120	0.1	60.71	0.819	18.114
12-	160	0.1	60.71	0.814	18.573
13-	20	0.17	57.14	0.803	19.623
14-	30	0.17	60.71	0.794	20.570
15-	40	0.17	60.71	0.790	20.961
16-	80	0.17	60.71	0.784	21.537
17-	120	0.17	60.71	0.744	25.538
18-	160	0.17	60.71	0.698	30.147

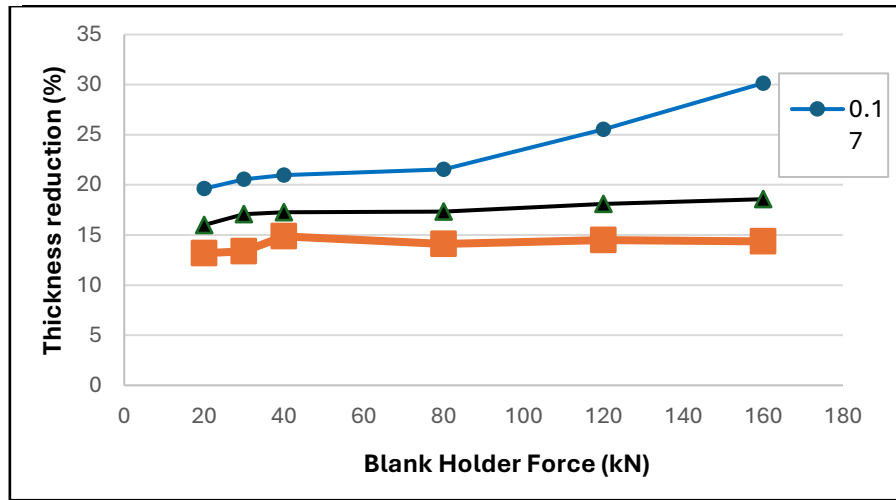


Figure 5. Effect of blank holder force on percentage thinning.

It has been stated by Halkacı et al. (2014) that a coefficient of friction of 0.05 between aluminum material and steel dies corresponds to experimental results. Therefore, the analysis results conducted with a coefficient of friction of 0.05 were taken into consideration when selecting the most suitable parameters. According to the blank holder force values tested, all force values in the range of 20 kN to 160 kN yielded nearly the same thinning values. However, when the blank holder force is low, there may be a risk of wrinkling in the sheet metal part. Therefore, the parts were evaluated for wrinkling at different force values using Isophote Analysis; according to the results obtained in Figure 6, it was observed that wrinkling in the flange region of the sheet metal part decreased at a force value of 120 kN, and thus it was considered the optimum value. Consequently, it was determined that a fluid pressure of 60 MPa and a blank holder force of 120 kN must be applied to form a part with an initial blank diameter of 230 mm and a bottom radius of 10 mm.

The FLD (Forming Limit Diagram) showing the forming limits of the 2024-T3 material was obtained from the study by Lee et al. (1997), as seen in Figure 7. Accordingly, it was concluded that the highest thinning in the material reached approximately 11% in the plane strain state, where the formability is at its lowest and the minor strain value is zero. Based on the thinning results obtained with a 10 mm bottom radius as shown in Figure 8, it was evaluated that it would not be possible to successfully produce the part with this selected radius value. Therefore, the part design has been updated.

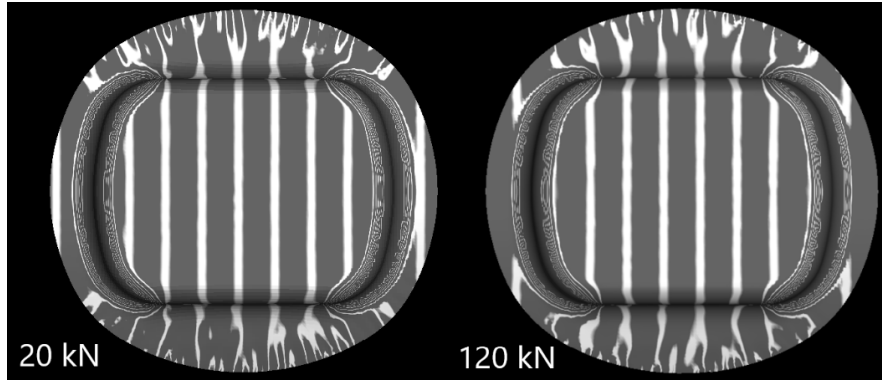


Figure 6. Isophote analysis for different blank holder forces.

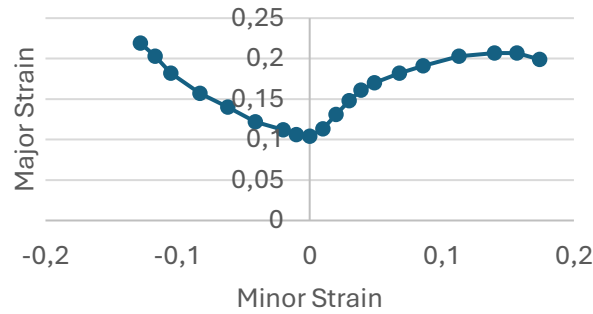


Figure 7. FLD of 2024-T3 aluminum material (Lee et al., 1997).

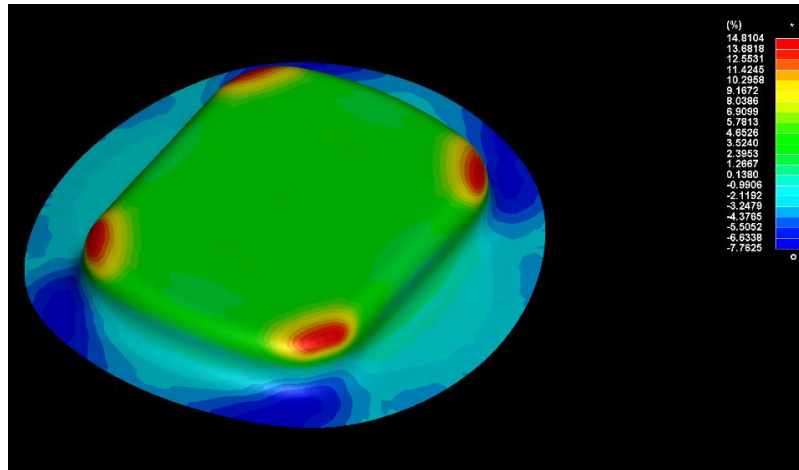


Figure 8. Thinning contours occurring at the base of the part.

Analyses were repeated for the case with the new diameter, a coefficient of friction of 0.05, and a blank holder force of 120 kN. In determining the new bottom radius value, the 600 kN clamping force of the hydroforming press located in the Hydroforming Laboratory at Konya Technical University, where the part will be produced, was also taken into consideration. During forming, forces resulting from fluid pressure and blank holder force act on the surface area of the female die. These forces must not exceed the capacity of the press used in the manufacturing process. According to the analysis results shown in Figure 9, when the vertical force distribution on the die reached the 600 kN limit ($s=0.007$); upon examining the cross-section of the die, sheet, and blank holder as shown in Figure 10, it was observed that the sheet had not yet seated in the female die and the desired geometry could not be achieved. In this case, it was determined that the part bottom radius should be 22 mm when the die is subjected to a 600 kN limit force. It was determined through analyses that for a part with a 22 mm bottom radius, the initial blank diameter must be 260 mm to maintain a minimum flange distance of 11.6 mm ($3D+2$, $D=3.2$) between the sheet edge and the part entry radius. In the new analysis, when the force-time graph acting on the die shared in Figure 11 for the case of an initial blank diameter of 260 mm and a radius of $R=22$ mm was examined, it was observed that the sheet metal part fully seated in the female die as shown in Figure 12, confirming that these parameters are suitable for manufacturing.

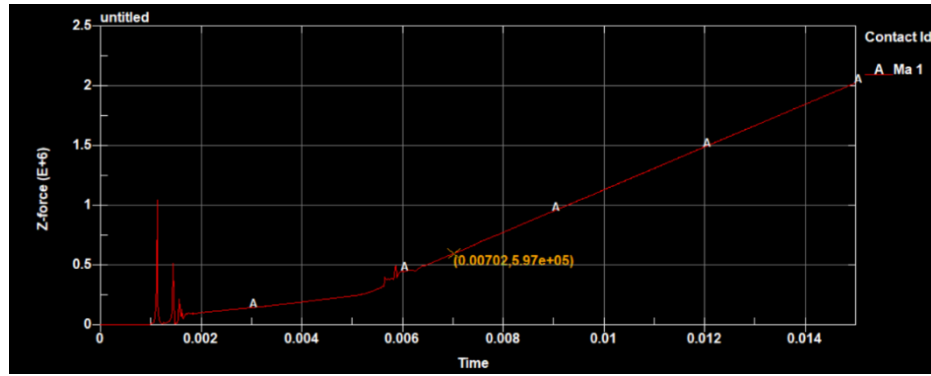


Figure 9. Time-force graph before the geometry update.

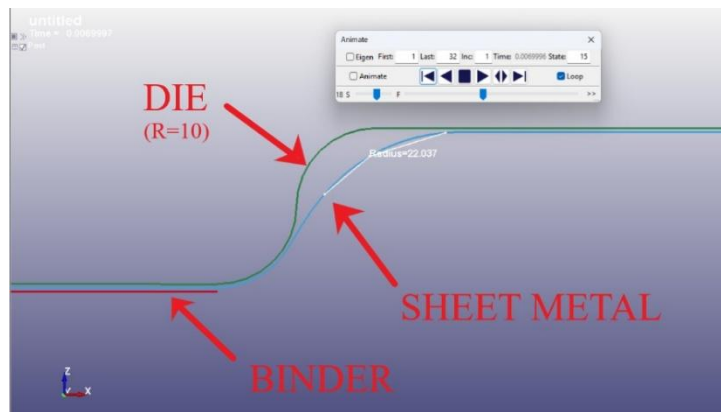


Figure 10. State of the sheet at the 60-ton limit before the geometry update.

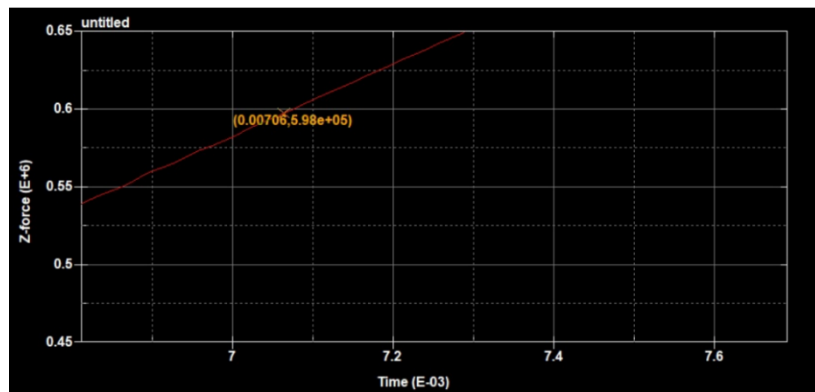


Figure 11. Force-time graph for the new analysis.

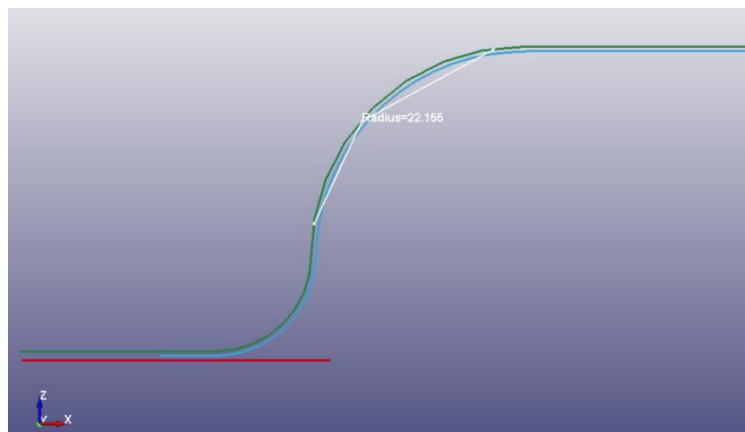


Figure 12. Final shape of the sheet in the analysis with an initial blank diameter of 260 mm and a bottom radius of 22 mm.

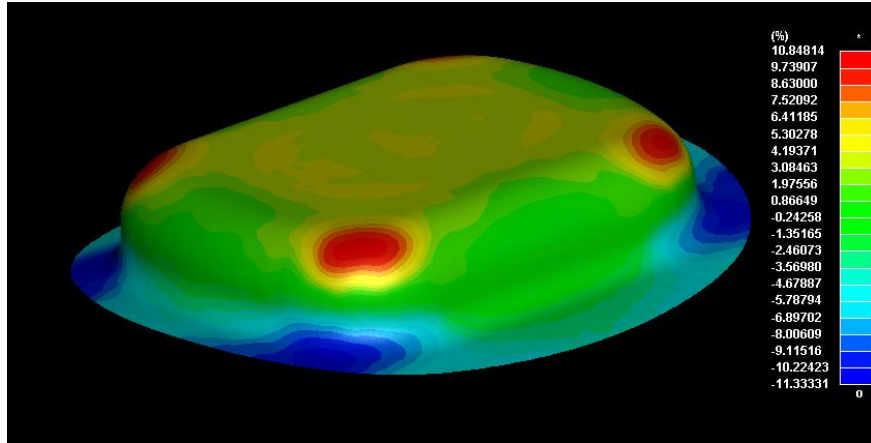


Figure 13. Thinning state determined in the final geometry.

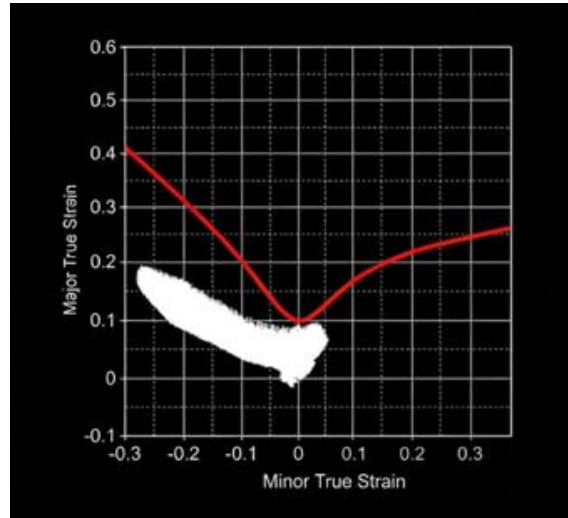


Figure 14. FLD (Forming Limit Diagram) for the updated geometry.

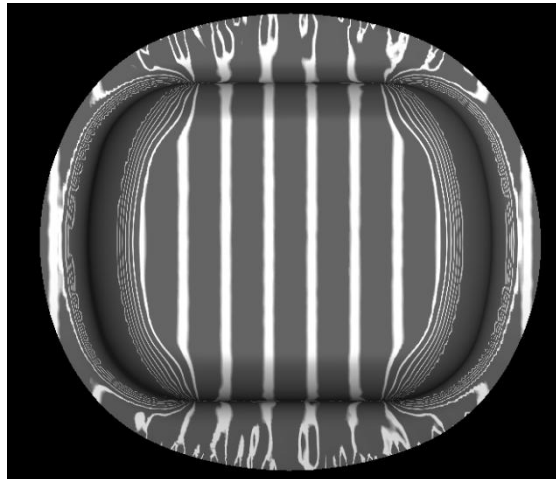


Figure 15. Isophote wrinkling analysis of the final geometry.

In conclusion, it was observed in the analyses conducted using the die with a bottom radius of 22 mm, 2024-T3 material with an initial blank diameter of 260 mm, and a blank holder force of 120 kN, that the sheet fully seated in the die. As shown in Figure 13, at a pressure of 6.75 MPa, the thinning value remained below 11%. When the strain distribution obtained from the part was plotted on the FLD of the material, as seen in Figure 14, all strain values remained below the forming limit curve. Therefore, it was concluded that the sheet metal part can be formed without failure using the identified parameters, and the part can be produced with an acceptable level of wrinkling in the outer flange diameter region according to the Isophote analysis in Figure 15. Thus, an interface part that

can be used for the connection of the Ga-58 commercial antenna to the helicopter tail has been designed, and the parameters for the successful production of the part through the hydroforming process have been determined.

Conclusion

In this study, the manufacturability of an interface part designed from 2024-T3 aluminum alloy to ensure the integration of the Ga-58 commercial antenna into the helicopter tail was investigated using the hydroforming method with a female die through Finite Element Analysis (FEA), and the process parameters were optimized. As a result of the iterative analyses conducted, the following key findings were obtained:

Effect of Friction and Blank Holder Force: It was observed that the most significant factor affecting the thinning of the sheet is the coefficient of friction. An increase in the coefficient of friction restricts the material flow into the die, thereby increasing the risk of tearing. Consistent with the literature, the most suitable coefficient of friction for the aluminum-steel interface was evaluated as 0.05. The optimum blank holder force that minimizes wrinkling defects (Isophote analysis) in the flange region was determined to be 120 kN.

Die Geometry and Press Capacity Constraints: In the analyses conducted with the initial design of a 10 mm bottom radius and a 230 mm initial blank diameter, it was observed that the maximum thinning in the part exceeded the 11% safe forming limit in the Forming Limit Diagram (FLD) of the 2024-T3 material. Additionally, under these parameters, the limits of the available hydroforming press with a 600 kN capacity were reached before the part could fully take its shape. This situation necessitated a revision in the part geometry.

Optimization and Successful Forming: Considering the press capacity and FLD limits, the part bottom radius was increased to 22 mm, and the initial blank diameter to 260 mm. In this optimized new design, analyses conducted under 33.75 MPa fluid pressure and 120 kN blank holder force showed that the sheet metal part fully seated in the die, the press limit force was not exceeded, and wrinkling remained at a tolerable level. Most importantly, the maximum thinning value remained below 11%, and all strain distributions were located within the safe zone of the FLD curve.

In conclusion, it has been proven that the 2024-T3 aluminum alloy, which is preferred in the aerospace industry due to its high strength but is difficult to form, can be successfully produced without tearing and wrinkling defects using the hydroforming method when proper die design and optimized process parameters are utilized. This study demonstrates that complex aerospace interface parts can be safely produced in fewer stages through hydroforming, instead of multi-stage conventional methods.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the author.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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Author(s) Information

Caner Türe

Konya Technical University Mechanical Eng. Department
Ardıçlı Mah. Rauf Orbay Cad. 42250,
Selçuklu/Konya/Türkiye
ORCID iD: <https://orcid.org/0009-0002-9550-4780>
Contact e-mail: canerture@outlook.com.tr

Batuhan Katırcı

Konya Technical University Mechanical Eng. Department
Ardıçlı Mah. Rauf Orbay Cad. 42250,
Selçuklu/Konya/Türkiye
ORCID iD: <https://orcid.org/0009-0006-6676-0792>
Contact e-mail: bthnkatirci@gmail.com

Mevlut Turkoz

Konya Technical University Mechanical Eng. Department
Ardıçlı Mah. Rauf Orbay Cad. 42250,
Selçuklu/Konya/Türkiye
ORCID iD: <https://orcid.org/0000-0001-9692-5777>
Contact e-mail: mturkoz@ktun.edu.tr

*Corresponding author(s) contact email

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ERP Strategic Framework for Vietnam's Precision Mechanical Engineering: A Hybrid MCDM Approach to Digital Transformation

Nhut TM Vo

Industrial University of Ho Chi Minh City

Abstract: For precision mechanical engineering firms in emerging economies, adopting an Enterprise Resource Planning (ERP) system presents a distinct challenge. Decision-makers frequently struggle to reconcile complex technical operational requirements with strict economic limitations. This research navigates this tension by developing a contextualized, mixed-methods evaluation framework for Vietnamese Small and Medium Enterprises (SMEs). Integrating qualitative expert consultation with a combined Best-Worst Method (BWM) and VIKOR analytical model, the study offers a rigorous, data-driven pathway to selecting the most viable ERP system. Applying BWM, the results indicate that Technical Capability emerges as the dominant evaluation criterion, substantially outweighing both Economic Feasibility and Organizational Readiness. The subsequent VIKOR compromise ranking further confirms Epicor Kinetic as the most suitable solution, as it provides the strongest overall performance (i.e., maximized group utility) while maintaining low individual regret—particularly in relation to complex requirements such as multi-level Bill of Materials (BOM) integration and Make-to-Order (MTO) synchronization. By contrast, alternatives emphasizing high modularity and lower upfront cost were ranked least favorable, primarily because they entail considerable operational risk in engineering-intensive settings. Taken together, these findings challenge conventional cost-led adoption logics and suggest an evidence-based implication for practice: decision-makers should prioritize foundational technical alignment over initial capital savings to enable a more resilient and sustainable digital transformation.

Keywords: Enterprise Resource Planning (ERP); Multi-Criteria Decision-Making (MCDM); Best-Worst method (BWM); VIKOR; Precision mechanical engineering.

Introduction

The global manufacturing landscape has been shifting in significant ways in recent years, with Vietnam increasingly positioned as a key node in the China-plus-one diversification strategy and a growing contributor to international supply chain networks (Basu & Ray, 2022). Within this evolution, the precision mechanical engineering sector stands as a cornerstone of the nation's industrial modernization. Unlike general manufacturing, this sector is defined by high-complexity environments—characterized by multi-level Bills of Materials (BOM), stringent quality tolerances, and a predominant Make-to-Order (MTO) production model. (Soeiro et al., 2025; Sun & Zhu, 2026). As these firms strive to integrate into global value chains, the transition toward Industry 4.0 is no longer optional; it is a strategic imperative for survival.

At the heart of this digital transformation lies Enterprise Resource Planning (ERP). For precision engineering firms, an ERP system serves as the digital nervous system, synchronizing shop-floor data with high-level administrative functions. However, the path to implementation is fraught with challenges. Statistics globally suggest that ERP implementation failure rates remain high, but the risk is amplified for Small and Medium Enterprises (SMEs) in emerging economies like Vietnam (Madathala et al., 2025). These firms often face a double bind: the technical necessity for sophisticated, real-time data integration versus the harsh realities of limited capital, legacy infrastructure, and a shortage of digital expertise.

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The existing literature frequently discusses ERP adoption in broad manufacturing contexts, yet there remains a significant gap in research tailored to the high-precision demands of the Vietnamese mechanical sector (Hing, 2025). Generic ERP solutions often fail to account for the nuances of local tax compliance, localized technical support needs, and the specific synchronization required between the shop floor and the warehouse in an MTO environment (Tran et al., 2026). While the potential of Artificial Intelligence (AI) for predictive maintenance and scheduling is widely recognized, its integration into the ERP ecosystems of Vietnamese SMEs remains underexplored (Hoang et al., 2025).

To address these gaps, this study proposes an integrated strategic framework for cloud-based ERP system selection and implementation. Drawing on a hybrid Multi-Criteria Decision-Making (MCDM) approach, the research identifies the critical success factors that separate a costly digital misstep from a meaningful operational transformation. The findings, informed by semi-structured interviews and supported by quantitative analysis, offer a contextually grounded roadmap aimed at helping Vietnamese supporting industries reduce lead times, improve supply chain transparency, and pursue a scalable, structured path through the broader complexities of digital transformation.

Literature Review

The successful deployment of Enterprise Resource Planning (ERP) in specialized industrial contexts requires a multidimensional understanding of technical capabilities, localized socio-economic barriers, and robust decision-science methodologies. (Akbari et al., 2024). This section synthesizes current academic discourse across three critical pillars to establish the theoretical foundation for the proposed framework.

Pillar 1: ERP in High-Precision Manufacturing

In the realm of precision mechanical engineering, ERP systems transcend basic administrative functions, acting instead as the primary engine for operational precision. Unlike mass production, precision engineering is characterized by Make-to-Order (MTO) strategies and extremely complex Bills of Materials (BOM) that require granular tracking.

Quality and Traceability: Research by Raiput et al. emphasizes that for high-precision sectors, ERP must support rigorous quality tolerances and "digital birth certificates" for components (Raiput et al., 2024). Compliance with ISO 9001 and IATF 16949 standards necessitates real-time traceability from raw material batch numbers to the final CNC machining parameters. (Razali et al., 2022).

Shop-Floor Synchronization: The integration of ERP with Manufacturing Execution Systems (MES) is a recurring theme in Industry 4.0 literature. Modern ERPs are expected to facilitate a "digital twin" environment where machine-level data—such as spindle hours or tool wear—is fed directly into the planning module to optimize production scheduling and minimize idle time. (Saenz de Ugarte et al., 2009; Vogel, 2026).

Material Complexity: Scholars argue that the primary failure point in engineering ERPs is the inability to manage engineering change orders (ECOs). A robust system must handle dynamic BOMs, with design modifications instantly reflected in procurement and floor-level instructions. (Bantwal & Fatahi Valilai, 2026).

The Digital Literacy Gap: Bilal et al. note that "technical debt" in Vietnam extends beyond old hardware to include human capital. There is a documented scarcity of personnel who possess both deep mechanical engineering knowledge and the digital fluency required to manage integrated systems (Bilal et al., 2026).

Legacy Reliance and Cultural Resistance: A significant proportion of Vietnamese enterprises continue to operate within fragmented "islands of information," characterized by a persistent reliance on disparate Excel-based tracking systems and siloed accounting software. Empirical evidence from recent industrial surveys indicates that cultural resistance—particularly the absence of a data-driven orientation among middle management—constitutes a more formidable barrier to digital transformation than the software's inherent technical complexities. (Nguyen et al., 2026; Nguyen & Kend, 2026).

Pillar 2: MCDM in System Selection: Beyond Financial Metrics

Selecting an appropriate ERP system is inherently complex, as it involves balancing a wide range of criteria that are often qualitative and often in tension with one another. In this regard, traditional Return on Investment (ROI) metrics have come to be seen as increasingly limited in their ability to capture long-term strategic value. A straightforward financial analysis, for instance, tends to overlook intangible yet consequential benefits—such as greater organizational transparency or stronger supplier relationships—that do not translate neatly into monetary terms. As a result, scholarly consensus has gradually shifted toward MCDM frameworks, which offer a more comprehensive and nuanced basis for evaluation.(Modi, 2026; Vo et al., 2023a).

Superiority of Hybrid Models: Hybrid MCDM models—such as those combining AHP with TOPSIS, or BWM with VIKOR—are particularly well-suited for navigating the inherent ambiguity that characterizes human judgment in complex decision-making contexts. The Best-Worst Method (BWM), for example, provides a structured mechanism for assigning relative weights to competing criteria, such as Local Vendor Support versus System Flexibility, in a way that is both systematic and cognitively manageable. Complementing this, the VIKOR method is designed to identify a compromise solution—one that performs reasonably well across all criteria—in situations where no single software alternative can simultaneously satisfy all requirements. Together, these approaches offer a more balanced and defensible basis for ERP selection than any single method could provide (Tang et al., 2026; Triantafyllidou & Vagiona, 2026).

Localized Weighting: A growing body of research suggests that when applying MCDM frameworks in emerging market contexts, localization criteria warrant considerably more attention than they typically receive in Western-oriented selection models. Factors such as compatibility with Vietnamese Accounting Standards (VAS) and the availability of native language support are not merely operational conveniences—they are foundational requirements that can significantly shape both adoption outcomes and long-term system usability. Yet these dimensions are frequently underweighted or overlooked in frameworks designed for more mature, Western institutional environments, highlighting a significant gap between existing models and the practical realities facing organizations in markets like Vietnam (Vo et al., 2023b; Wang et al., 2024).

Synthesis of Research Gaps

While the literature provides a clear view of ERP's technical requirements and the general hurdles in Vietnam, there is a notable absence of an integrated roadmap that specifically links MCDM-based selection to the MTO-specific workflows of precision engineering. Existing research is often siloed into either purely technical discussions or broad economic analyses. This study bridges these gaps by proposing a localized framework that harmonizes the technical demands of Industry 4.0 with the practical resource constraints of the Vietnamese mechanical sector.

Method

This research adopts a mixed-methods design, synthesizing qualitative expert heuristics with quantitative decision-analytic modeling to formulate a contextualized ERP implementation framework for the precision mechanical engineering sector. The methodological architecture is partitioned into three discrete phases: (1) Criteria Identification and Alternative Selection: This initial stage involves the identification of critical evaluative criteria through expert consultation, coupled with the preliminary selection of ERP alternatives specifically tailored to the requirements of high-precision manufacturing. (2) Hybrid MCDM Modeling: This phase leverages hybrid MCDM modeling to establish a systematic weighting of criteria, ensuring that the evaluation transcends purely financial metrics. (3) Alternative Ranking: The final phase focuses on the execution of a compromise ranking of the selected alternatives to determine the optimal solution for the target industrial environment.

Phase I: Criteria Identification and Alternative Selection

To understand the unique operational realities of high-precision engineering, the first phase of this study involved semi-structured interviews with five industry experts. Drawing on their localized experience, this consultative approach helped identify four core evaluative criteria specifically suited to the Vietnamese manufacturing sector. By bringing together academic theory and practical, on-the-ground insights, the resulting framework bridges a critical gap: it balances the strict technical demands of complex manufacturing—such as multi-level BOM synchronization—with the financial realities and organizational readiness of domestic Small and Medium Enterprises (SMEs). Ultimately, these four criteria serve as the foundation for the hybrid BWM-VIKOR decision-

making model, ensuring the system evaluation goes beyond basic cost analysis to capture what these firms genuinely need to succeed:

(C1) Technical Capability: This dimension prioritizes the synchronization of multi-level Bills of Materials (BOM), which is essential for managing the high-complexity Make-to-Order (MTO) workflows inherent in precision machining (Soeiro et al., 2025; Sun & Zhu, 2026).

(C2) Economic Feasibility: Evaluation focuses on the comprehensive Total Cost of Ownership (TCO), accounting for both direct capital expenditures and hidden implementation costs (Nguyen et al., 2025). **(C3)**

Vendor Reliability: This criterion emphasizes the necessity of localized technical infrastructure and support ecosystems to ensure system stability within the Vietnamese regulatory environment (Tran et al., 2026). **(C4)**

Organizational Readiness: This final dimension assesses the digital maturity and analytical capacity of the human capital, addressing the critical "digital literacy gap" that often moderates implementation success (Adel, 2024; Huynh et al., 2025).

Phase II: Expert-Driven Evaluative Scaling and Empirical Validation

Unlike the traditional Analytic Hierarchy Process (AHP), which necessitates pairwise comparisons, the BWM optimizes the process by requiring only $\frac{n(n-1)}{2}$ comparisons. Decision-makers are tasked with identifying the "Best" (most significant) and "Worst" (least significant) criteria, subsequently comparing all other attributes against these two reference points. This approach substantially mitigates cognitive load and the potential for human error—critical factors when eliciting data from high-level manufacturing executives in a time-constrained industrial environment (Bhattacharjee et al., 2022; Khokhar et al., 2020). The final phase of this research involves empirically validating the proposed framework through a structured expert evaluation process. To ensure rigorous assessment of the Multi-Criteria Decision-Making (MCDM) outputs, a panel of experts from the surveyed precision engineering firms was tasked with providing evaluations on a standardized 9-point scale. This 9-point scale facilitates the translation of qualitative linguistic judgments into precise numerical values, with 1 indicating "Equal Importance/Effectiveness" and 9 "Extreme Importance/Effectiveness" (Rezaei, 2015).

Phase III: Alternative Ranking

After establishing the criteria weights, the VIKOR (VlseKriterijumska Optimizacija I Kompromisno Resenje) method is used to rank ERP solutions. VIKOR is particularly robust for this study as it determines a "compromise solution" by maximizing group utility (overall system performance) while simultaneously minimizing individual regret (ensuring that non-negotiable requirements, such as localized tax compliance, are satisfied) (Chiu et al., 2013; Titiyal et al., 2019).

Results and Discussion

Enhanced Operational Transparency and Lead Time Reduction

Table 1. Fundamental scale of importance for MCDM evaluation

Rating	Linguistic Definition / Meaning
1	Equal importance
2	Somewhat between Equal and Moderate
3	Moderately more important than
4	Somewhat between Moderate and Strong
5	Strongly more important than
6	Somewhat between Strong and Very strong
7	Very strongly important than
8	Somewhat between Very strong and Absolute
9	Absolutely more important than

To systematically translate qualitative expert judgments into a quantifiable format for mathematical modeling, this study utilizes a standardized 9-point fundamental scale. This scale acts as a vital bridge between subjective linguistic preferences and objective numerical data. By doing so, it enables a precise calculation of each criterion's relative importance within the hybrid MCDM framework. *Table 1* delineates the numerical ratings and their corresponding linguistic definitions, providing the methodological basis for the criteria weighting and alternative ranking processes executed in the BWM and VIKOR phases.

Following the synthesis of expert judgments and the subsequent mathematical derivation of criteria weights, a distinct hierarchical prioritization emerged among the four primary dimensions of the strategic framework. Technical Capability was identified as the most critical determinant, with a significant weight of 0.4286, underscoring the sector's paramount need for multi-level BOM synchronization and MTO workflow management in high-precision environments. Economic Feasibility and Vendor Reliability were of equal secondary importance, each assigned a weight of 0.2571, reflecting a balanced strategic focus between managing total cost of ownership and ensuring robust, localized technical support. Conversely, Organizational Readiness was determined to be the least influential factor, yielding a weight of 0.0571, suggesting that while the digital maturity of human capital is essential for implementation, it is perceived as a subordinate priority relative to the system's core functional and economic viability during the initial selection phase. These calculated weight distributions are graphically represented in *Figure 1*.

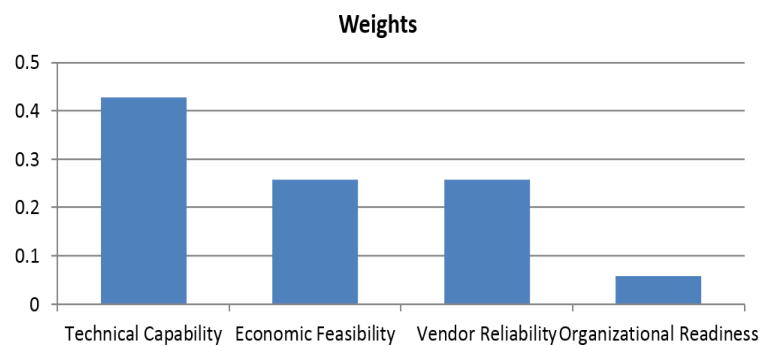


Figure 1. Distribution of calculated weights for ERP selection criteria

Table 2 presents the consolidated decision matrix, which synthesizes the expert panel's qualitative assessments across the four primary evaluative dimensions. Using the 1–9 fundamental scale, these linguistic judgments were converted to precise numerical values to facilitate the subsequent VIKOR-based compromise ranking analysis. This matrix provides the quantitative basis for evaluating each ERP alternative against the sector-specific requirements of Vietnamese precision engineering firms.

Table 2. Consolidated expert decision matrix

Alternative	C1	C2	C3	C4
A1: SAP S/4HANA	8.8	3.2	8.5	4.5
A2: Oracle NetSuite	7.5	5.8	7.8	6.2
A3: Epicor Kinetic	8.2	4.5	7.2	5.5
A4: Odoo	5.5	8.6	6.5	8.4
A5: Infor SyteLine	7.8	5.2	7.5	6.0

Table 3 demonstrates that the final computational phase of the VIKOR methodology yields the indices for maximum group utility (S), minimum individual regret (R), and the comprehensive compromise ranking measure (Q) for each ERP alternative. As evidenced by the calculated results, Alternative A3 (Epicor Kinetic) clearly emerges as the optimal compromise, achieving the lowest possible Q value of 0. This definitive ranking is fundamentally driven by its simultaneous minimization of both the S index (0.300182) and the R index (0.095455).

In decision-science terms, this indicates that A3 successfully maximizes the overall operational utility for the majority of the criteria while rigorously minimizing the regret associated with individual criterion underperformance. Alternative A5 (Infor SyteLine) secures second place with a Q value of 0.239055, further underscoring the sector's strategic preference for systems inherently specialized in complex engineering and BOM workflows. Conversely, Alternative A4 (Odoo), despite its initial appeal on economic feasibility, ranks lowest with a Q value of 1. This reflects a significantly higher degree of implementation risk and system inadequacy when evaluated against the stringent technical demands of the precision mechanical environment.

Table 3. Final VIKOR evaluation metrics and compromise ranking results

Alternative	S	R	Q
A1	0.363636	0.272727	0.424883
A2	0.511077	0.177273	0.466204
A3	0.300182	0.095455	0
A4	0.636364	0.363636	1
A5	0.409632	0.136364	0.239055

The VIKOR indices visually reinforce the hierarchical standing of the evaluated ERP systems. As depicted, Alternative A3 demonstrates unambiguous superiority by minimizing both the maximum group utility distance (S) and the individual regret metric (R), converging on the optimal Q value of 0. *Figure 2* disparity underscores A3's balanced capability to satisfy the aggregated criteria while effectively mitigating specific operational risks. In stark contrast, Alternative A4 exhibits the greatest deviation from the ideal solutions across all parameters, solidifying its position as the least viable option for this high-precision industrial context. Furthermore, the chart clearly shows that Alternative A5 is the most competitive runner-up, with comparatively low indices for both individual regret (R) and the final compromise measure (Q).

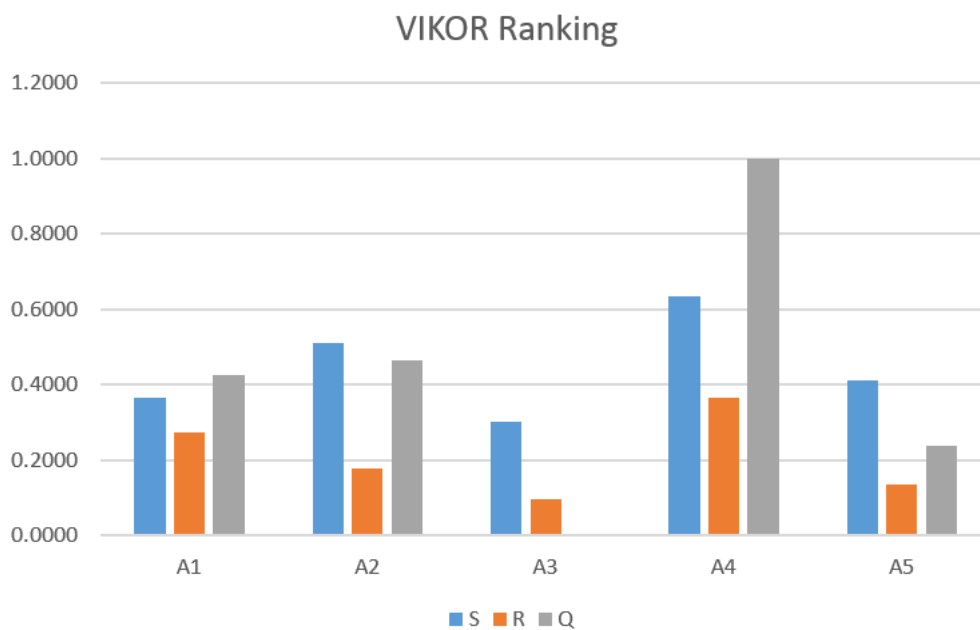


Figure 2. Final compromise ranking results of ERP alternatives

Discussion

The empirical results of this study illuminate the complex trade-offs inherent in selecting an Enterprise Resource Planning (ERP) system for the precision mechanical engineering sector. The criteria weighting derived from the Best-Worst Method (BWM) establishes that Technical Capability (0.4286) is the paramount concern for industry experts. This heavy prioritization validates the hypothesis that high-tolerance manufacturing environments cannot compromise on core operational functionalities, specifically multi-level Bill of Materials (BOM) synchronization and Make-to-Order (MTO) workflow management. The VIKOR compromise ranking provides critical insights into the viability of market-leading ERP solutions within this specific industrial context. Alternative A3 (Epicor Kinetic) emerged as the unequivocal optimal solution ($Q = 0$). Its success is fundamentally due to its ability to meet the stringent technical requirements of the sector while maintaining an acceptable threshold for Economic Feasibility and Vendor Reliability. In contrast, Alternative A4 (Odoo), which often appeals to Small and Medium Enterprises (SMEs) due to its superior Economic Feasibility and Organizational Readiness, ranked as the least viable option ($Q = 1$). This dichotomy highlights a critical industry reality: cost-efficiency and user-friendly interfaces cannot compensate for foundational inadequacies in handling complex engineering data. The high individual regret metric (R) associated with Odoo suggests that adopting a generic, modular system poses significant operational risks in high-precision environments.

Similarly, while Alternative A1 (SAP S/4HANA) possesses robust technical capabilities, its lower overall ranking compared to A3 and A5 (Infor SyteLine) reflects the inhibiting nature of its high Total Cost of Ownership (TCO) and potential localized support challenges. Therefore, the VIKOR analysis demonstrates that the optimal ERP for this sector is not necessarily the most technologically advanced or the most affordable, but rather the one that offers the best balance between rigorous technical alignment and systemic feasibility.

Conclusion

This research successfully developed a localized, data-driven ERP selection framework tailored specifically for the precision mechanical engineering sector. By transitioning away from heuristic, intuition-based decision-making, the study employed a robust mixed-methods design integrating qualitative expert consultation with quantitative decision-science modeling.

The application of the BWM optimized the criteria weighting process, significantly reducing the cognitive load on subject matter experts while accurately capturing the sector's operational priorities. The subsequent VIKOR analysis provided a rigorous mathematical validation of the alternatives, ultimately identifying Epicor Kinetic (A3) as the optimal compromise solution, closely followed by Infor SyteLine (A5). The study concludes that for precision manufacturing firms, the successful adoption of Industry 4.0 technologies hinges primarily on a system's technical capability to manage complex, customized production workflows, rather than on upfront capital savings. Ultimately, this framework bridges the gap between legacy operational paradigms and digital transformation, offering a highly contextualized roadmap for Vietnamese SMEs navigating complex software investments.

Recommendations

Based on the synthesized findings and the hierarchical ranking of the evaluative criteria, several strategic recommendations are proposed for industry stakeholders and the academic community. For manufacturing executives and practitioners, it is imperative to prioritize technical alignment over initial cost savings. Decision-makers must actively avoid the cost trap of low-cost, generic ERP systems and strictly anchor their selection in a system's inherent capacity to manage high-complexity MTO workflows and intricate BOMs. Furthermore, firms should transition away from ad hoc software selection processes and adopt structured MCDM frameworks, such as the BWM-VIKOR model, to objectively navigate conflicting operational, economic, and human capital variables. For ERP vendors and integrators, enhancing localized ecosystems is paramount. Given the significant weight (0.2571) assigned to Vendor Reliability, global providers must invest heavily in localized technical infrastructure, as ensuring seamless compliance with regional requirements—such as Vietnamese Accounting Standards (VAS)—constitutes a critical competitive advantage. Additionally, vendors of high-tier, technically robust systems like SAP or Epicor should explore modular, Cloud-based SaaS architectures to lower the upfront Capital Expenditure (CAPEX) barriers for high-growth SMEs. Finally, to advance future research, subsequent studies should consider methodological expansions by integrating Fuzzy Logic or Neutrosophic sets into the existing BWM-VIKOR framework to better capture and quantify the inherent ambiguity and uncertainty in expert linguistic evaluations. Moreover, while this study focuses primarily on the selection phase, future inquiries must conduct longitudinal post-implementation analyses on the recommended systems to empirically validate the projected improvements in lead time reduction and operational transparency.

Scientific Ethics Declaration

* The author declares that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the author.

Conflict of Interest

* The author declares that there is no conflict of interest

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Author(s) Information

Nhut TM Vo

Industrial University of Ho Chi Minh City, Vietnam
No. 12 Nguyen Van Bao, Hanh Thong Ward, Ho Chi Minh City,
Vietnam

ORCID iD: <https://orcid.org/0000-0003-1990-749X>

*Contact e-mail: vothiminhnhut@iuh.edu.vn

*Corresponding author(s) contact email

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Evaluation and Comparison of the Seismic and Environmental Performance of Plane Trusses and Flat Space Frames: A Parametric Study on Soil and Climatic Influence

Siamak Aghaei

Yildiz Technical University

Ali Koken

Konya Technical University

Abstract: This study evaluates the analysis and design of two steel roof structures according to current practices in Turkey, including Eurocode 1 (2007) and the Turkish Building Earthquake Code of 2018 (TBEC 2018), with the aim of comparing the efficient roof system configuration from both a structural perspective and a structural behavior perspective. In this study, 8 structural models were examined, which investigated a combination of 2 different structural roof types, Plane Trusses (Type A) and Flat Space Frames (Type B), in two different climatic regions (Zone II and Zone IV), one seismic level, and two site classes (ZB and ZC). Structural modelling and analyses were analyzed and simulated using SAP2000 software. Calculations were carried out in accordance with the Turkish Steel Structures Design, Calculation and Construction Regulations (SDCCSS, 2016). The results indicate that the sensitivity of the structure to lateral loads is largely dependent on the classification of the lands and soil types, so that for type II lands, wind-induced displacements predominate, while for zone IV lands and site class (ZD), the behavior of the structure changes and becomes earthquake-oriented, with seismic displacements being predominant. Economically, Type A systems achieved the maximum weight for 20 m spans, and Type B systems recorded the minimum material consumption. Seismic displacements were recorded at higher levels for ZC site class, as well as for all models 2 and 4. This study shows that the choice of roof geometry significantly affects the total weight of the structure and consequently the cost of the project. The results of the analysis confirm that the performance of the Type B systems in limiting the lateral displacement in weak soils.

Keywords: Space truss system, Plane truss performance, Industrial buildings, Comparative analysis, Site class

Introduction

Roof structures are among the most significant structural members in buildings. They have a significant influence on load transfer. Recently, comparisons of plane trusses and space frames have attracted attention due to differences in seismic and environmental performance (Utami et al., 2025; Wang et al., 2025). Flat trusses, due to their simple structure, have been widely used in buildings. However, they have shown greater sensitivity to changes in soil conditions and seismic forces (Aydoğdu et al., 2023). On the other hand, space frames have shown better performance in buildings due to the use of multidimensional connecting members, which can help reduce material consumption (Utami et al., 2025). Studies have shown that the effects of optimization in design and material selection, including consideration of soil-structure interaction and climatic conditions, can significantly affect the final weight and stability of the structure (Prakash et al., 2024; Aydoğdu et al., 2023).

The use of optimization techniques such as Particle Swarm Optimization (PSO) and Ant Colony Optimization (ACO) can lead to lighter, more robust structural systems (Carbas & Tunca, 2023). Furthermore, techniques

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such as curved-crease origami-inspired foldable nodes in space frames can lead to cost savings during construction and increased design flexibility (Lee et al., 2025). With regards to seismic activity and environmental sustainability in roof structure design, a parametric analysis of the effects of soil types and climate on plane trusses and space frames can provide a comprehensive guide to selecting the best possible structural system. This analysis is significant in modern engineering designs as it considers various loads and roof slopes (Baranyai, 2018; Cucuzza et al., 2023).

Method and Analysis

Structural Models and Design Parameters

In this study, we investigate the seismic and environmental performance of industrial buildings in Turkey under different environmental and seismic conditions, focusing on how soil and climate affect these structures. Eight computational models were developed to analyze two different steel roof systems. One is “Plane Trusses”, a 2D truss structure used for sloping roofs (slope 11.31°) and the other is “Flat Space Frames”, a 3D lattice structure. The dimensions of the buildings were considered constant as 42 m x 20 m x 8 m (length x width x height) and also two different climatic regions were selected with zone II in Tekirdag city and zone IV in Bursa city. The column bases were assumed fixed in the analyses and two soil profiles were considered for each model, including site classes ZB and ZC, which are equivalent to site classes D and C of the ASCE 7 code. A summary of the eight simulation scenarios is given in Table 1.

Table 1. General configuration and variables of the research models

Model ID	Roof System Type	Climate Region	Site Classes	Seismic Level (SDS)	Roof Slope (α)
A1	Plane Truss	II	ZB	SDS>0,75	11.31°
A2	Plane Truss	II	ZC	SDS>0,75	11.31°
A3	Plane Truss	IV	ZB	SDS>0,75	11.31°
A4	Plane Truss	IV	ZC	SDS>0,75	11.31°
B1	Space Frame	II	ZB	SDS>0,75	0.00°
B2	Space Frame	II	ZC	SDS>0,75	0.00°
B3	Space Frame	IV	ZB	SDS>0,75	0.00°
B4	Space Frame	IV	ZC	SDS>0,75	0.00°

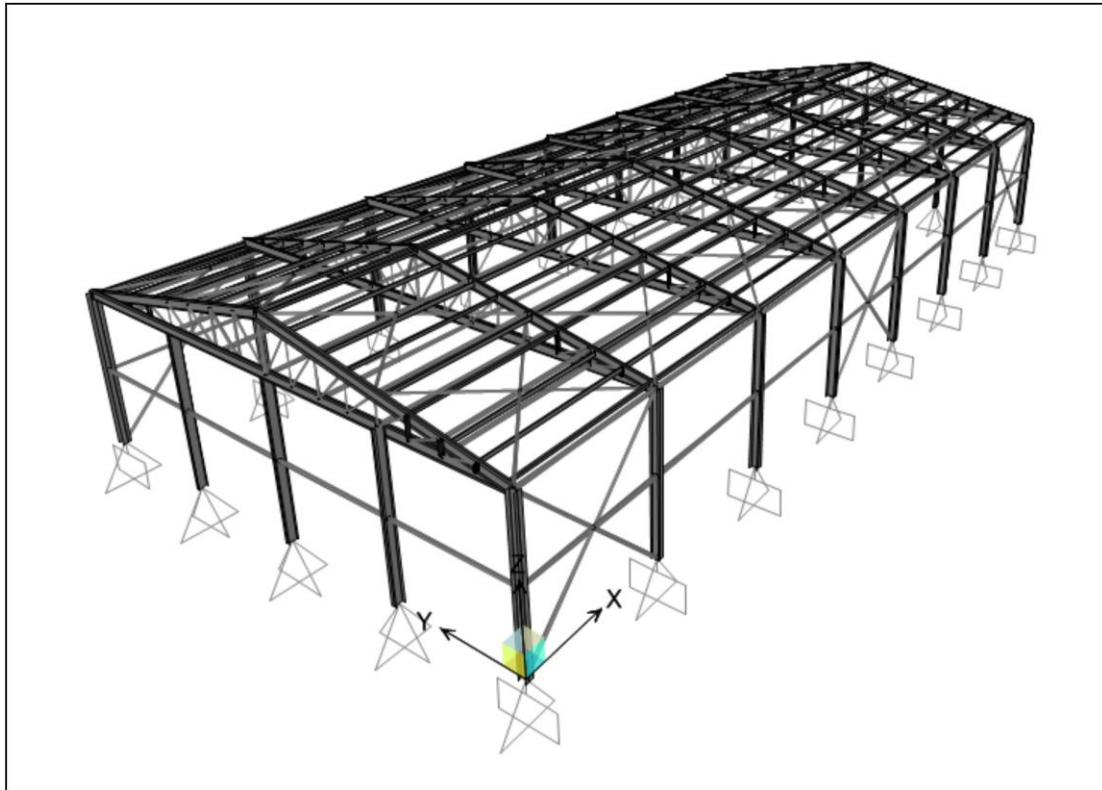


Figure 1. Three-dimensional view of double-pitch truss structural system

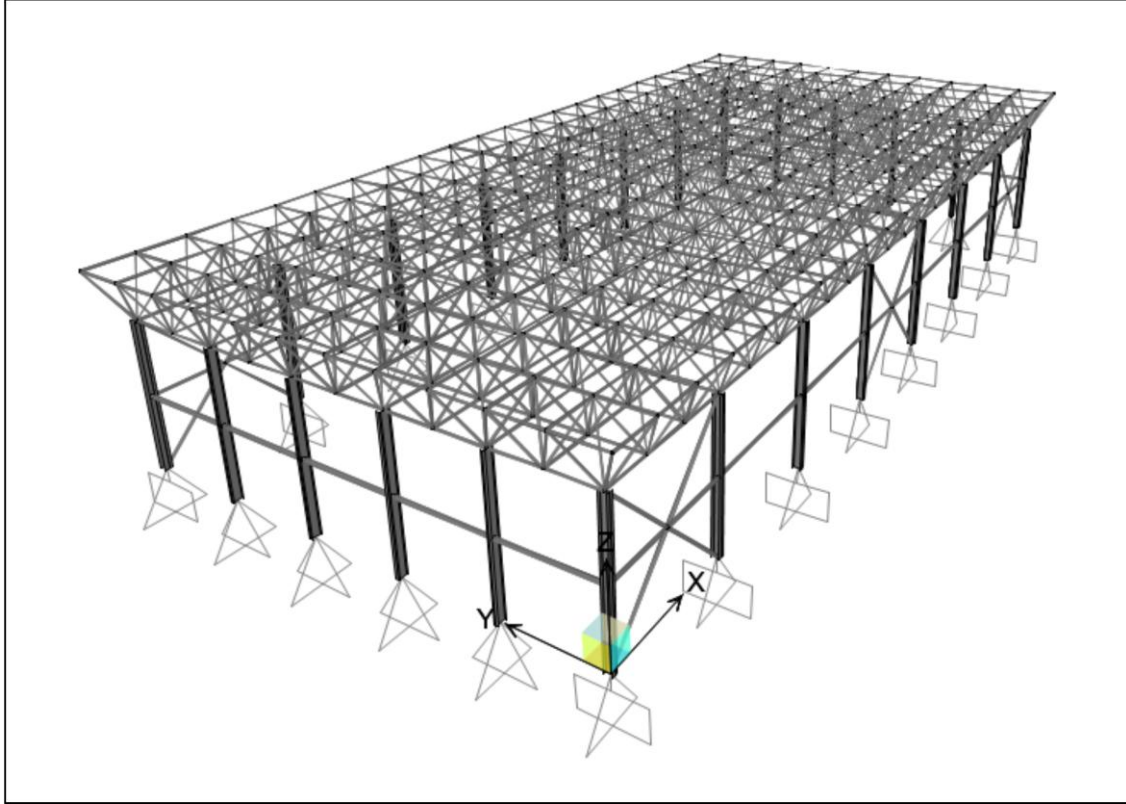


Figure 2. Three-dimensional view of the flat space frame system

Structural Modeling, Analysis, and Loading Conditions

In this study, geometric modeling and structural analyses were performed using SAP2000 software, considering linear material behavior for steel members. Gravity and wind loads were applied in accordance with Turkish Standard TS EN 1991-1-4 (Eurocode 1, 2007), and for seismic analyses, the Turkish Building Earthquake Code (TBEC, 2018) was used. The design of steel members was carried out according to the Turkish Specification for Design, Calculation and Construction of Steel Structures (SDCCSS, 2016) using the Load and Resistance Factor Design (LRFD) method. The main focus of this method is on the combination of loads and the safety factor for lateral loads and soil effects, which is aimed at investigating how soil and weather affect these structures. Since the purlins were modeled in the structure, the purlins load was not considered. A cladding load of 0.10 kN/m^2 was applied to the roof, and as dead load, cladding load and girt load, 0.30 kN/m^2 was applied to the facade columns. Live loads were applied based on the intended use of the building and a temporary design load of 1.00 kN/m^2 was applied. In order to consider the ambient temperature changes, thermal loads were applied to the structure. The structural members were designed considering temperature changes of $\pm 20^\circ\text{C}$, which were considered to reflect the expected operational and climatic conditions.

In order to evaluate the structural response under snow loads, Bursa and Tekirdag were selected as sample industrial sites. Although these cities differ in altitude above sea level, they are classified to the same snow load category according to the Turkish Standard TS EN 1991-1-3 (Eurocode 1, 2007). Considering the roof slopes of 0° and 11.31° , the shape factor μ_i was taken as 0.8 according to TS EN 1991-1-4 (Eurocode 1, 2007). A summary of the parameters used for calculating the design snow load is given in Table 2, where the snow load was calculated using equation (1).

Table 2. Design parameters for snow load calculation based on TS EN 1991-1-4 (Eurocode 1, 2007)

Parameter	Symbol	Value
Characteristic ground snow load	S_k	0.75 kN/m^2
Snow shape coefficient	μ_i	0.80
Exposure coefficient	C_e	1.00
Thermal coefficient	C_t	1.00
Design Snow Load	S	0.60 kN/m^2

$$S = \mu_e \times C_e \times C_i \times S_k \quad (1)$$

Seismic Load Modeling and Analysis

The seismic design of the structure was carried out in accordance with the Turkish Building Earthquake Code (TBDY 2018) considering the seismic hazard level DD-2, which indicates a moderate earthquake hazard, which is approximately in line with the Design Base Earthquake (DBE) in ASCE 7 standards. Two site classes, ZB and ZC, which are equivalent to the two site classes D and C of the American Society of Civil Engineers ASCE 7 code. The main seismic design parameters and coefficients used in the structural system are summarized in Table 3 and Table 4. The analyses were performed using the modal combination method and the results were verified against the Equivalent Seismic Load Method. The classification of this building according to the Turkish Building Earthquake Code (TBDY 2018) is BKS-3 category with an importance factor $I=1.0$, which is equivalent to the American Society of Civil Engineers code ASCE 7 Risk Category II. The building height is 8 meters (HN), which is earthquake design category 2 (DTS 2) according to the code and falls within the height range of $7.0 \leq HN < 10.5$ meters. Accordingly, the building height category (BYS) is considered to be 7. Seismic parameters were determined in accordance with TBDY 2018 and the guidelines of the Turkish Steel Structure Design Code (SDCCSS-2016) were used for load combinations, modeling and analysis of steel members. In order to consider the nonlinear effects of the structure and its energy absorption capacity, seismic force reduction factor (R) and overstrength factor (D) were considered in accordance with SDCCSS-2016 for the X and Y directions. Vertical seismic effects ($E_d(Z)$) were included in the load combinations as recommended by the code.

Table 3. Seismic design parameters and structural response factors [20]

Description	Symbol	Value
Earthquake Ground Motion Level	-	DD-2
Local Soil Class	-	ZC
Short-period design spectral acceleration	SDS	1.003
1.0s period design spectral acceleration	SD1	0.342
Building Importance Factor	I	1.0
Seismic Design Category	DTS	1
Building Height Class	BYS	7
Response Modification Coefficient (X / Y)	R	5 / 8
Overstrength Factor (X / Y)	D	2 / 3

Table 4. Seismic design parameters and structural response factors [20]

Description	Symbol	Value
Earthquake Ground Motion Level	-	DD-2
Local Soil Class	-	ZD
Short-period design spectral acceleration	SDS	0.752
1.0s period design spectral acceleration	SD1	0.182
Building Importance Factor	I	1.0
Seismic Design Category	DTS	1
Building Height Class	BYS	7
Response Modification Coefficient (X / Y)	R	5 / 8
Overstrength Factor (X / Y)	D	2 / 3

Wind Load Modeling and Analysis

For all eight structural models, wind loads were determined according to TS EN 1991-1-4 (Eurocode 1, 2007). The peak velocity pressure (q_p) was Calculated to be 1.08 kN/m^2 for structures in Region II and 0.51 kN/m^2 for Region IV, as shown in Table 5. The net wind pressure (W_{net}) on the surface of the structure was calculated using Formula 2. In this formula, $C_{p,net}$ represents the net pressure coefficient, and q_p represents the wind velocity pressure at height z . The surface of the wall and roof was divided into standard pressure zones A to E, and $C_{p,net}$ and branch dimensions of $e/4$ and $e/10$ were used to accurately determine the spatial change in wind suction and pressure. The external pressure coefficients (C_{pe}) were applied depending on roof geometries for pitched and flat roof systems. For the pitched roof models with a slope angle of 11.31° , the external pressure coefficients (C_{pe}) were determined for both wind directions ($\theta = 0^\circ$ and $\theta = 90^\circ$), i.e., the two directions (X and Y) in accordance with TS EN 1991-1-4 (Eurocode 1, 2007). Since this regulation provides values for roof slopes

of 5° and 15°, linear interpolation was used to obtain the coefficients for the actual roof angle. Due to the fluctuating nature of the wind, positive and negative pressure effects were considered. For the wind perpendicular to the overhang ($\theta = 0^\circ$), the roof was divided into four standard pressure zones (F to I), while for the wind direction parallel to the overhang ($\theta = 90^\circ$), the roof was divided into five main zones (F to G), all of which were mainly subjected to suction, and critical pressure values were observed near the edge zones (F and G). The peak velocity pressure (q_p) was significantly higher in zone II than in zone IV, indicating more severe wind effects in this region. For each direction, external pressure coefficients (C_{pe}) and internal pressure coefficients (C_{pi}) were considered. Internal pressure coefficients were calculated based on the size and distribution of openings in industrial structures to ensure that the combined effect of external suction and internal pressure on the roof and wall cladding is correctly accounted for in the structural analysis.

For flat roof models, external pressure coefficients ($C_{pe,10}$) were determined assuming sharp edges and the zoning parameter was defined by the formula $e = \min(b, 2h)$ which was calculated according to the structural information $e = 16m$.

$$W_{net} = q_p(z) \times (c_{pe} - c_{pi}) \quad (2)$$

Table 5. Summary of wind design parameters

Parameter	Symbol	Region II (A1-B2)	Region IV (A3-B4)
Basic wind velocity	v_b	28 m/s	28 m/s
Roughness factor	$c_r(z)$	0.96	0.49
Turbulence intensity	$I_v(z)$	0.2	0.48
Exposure coefficient	$c_e(z)$	2.21	1.04
Peak velocity pressure	$q_p(z)$	1.08 kN/m ²	0.51 kN/m ²

The selected cross-sections for all model A-1 and B1 are summarized in Tables 6.

Table 6. Sections for Models A-1 and B-1

Structural Element	Model A-1 Sections	Model B-1 Sections
Compression Pipe (Y)	CHCF139.7X5	CHCF139.7X5
Compression Pipe (X)	-	CHCF168.3X5
Roof Bracing	CHCF88.9X3.5	-
Facade Bracing	CHCF114.3X5	CHCF114.3X3.6
Main Column	HE280B	HE280B
Wind Column	IPE360	IPE360
Gable Post	HE100A	-
Truss Member	CHCF60.3X3.6	CHCF76.1X2.5
Roof Purlin	UPN120	-
Bottom Chord	IPE330 (Beam)	CHCF88.9X3.2
Top Chord	IPE330 (Beam)	CHCF88.9X3.2
Total Weight	56.48 tons	39.67 tons

Results and Discussion

Seismic Interstory Drift Analysis

As you can see in Figure 3, for two structural system models, namely Model A (plate truss) and Model B (space frame), the relative displacement index of the stories (Δ/h) in seismic zones II and IV and soil classes ZB and ZC in the critical Y direction has been compared. Based on the results we obtained, all configurations have fully complied with the 0.008 limit set by the TBDY-2018 regulations. Data analysis shows that, with the transition from seismic zone II to IV and the weakening of the site class from ZB to ZC, lateral displacement has increased in both models. Although in most cases, due to the higher rigidity of the space frame system, Model B has recorded less drift than Model A, in critical conditions IV-ZC, both Models A and B have approached the upper limits; So that Model A responded with a value of 0.0069 (86% of the allowable limit) and Model B responded with a value of 0.0063 (79% of the allowable limit). Therefore, the results obtained confirm that the space frame system provides greater lateral stability and a wider safety margin in softer soils and areas with high seismic risk.

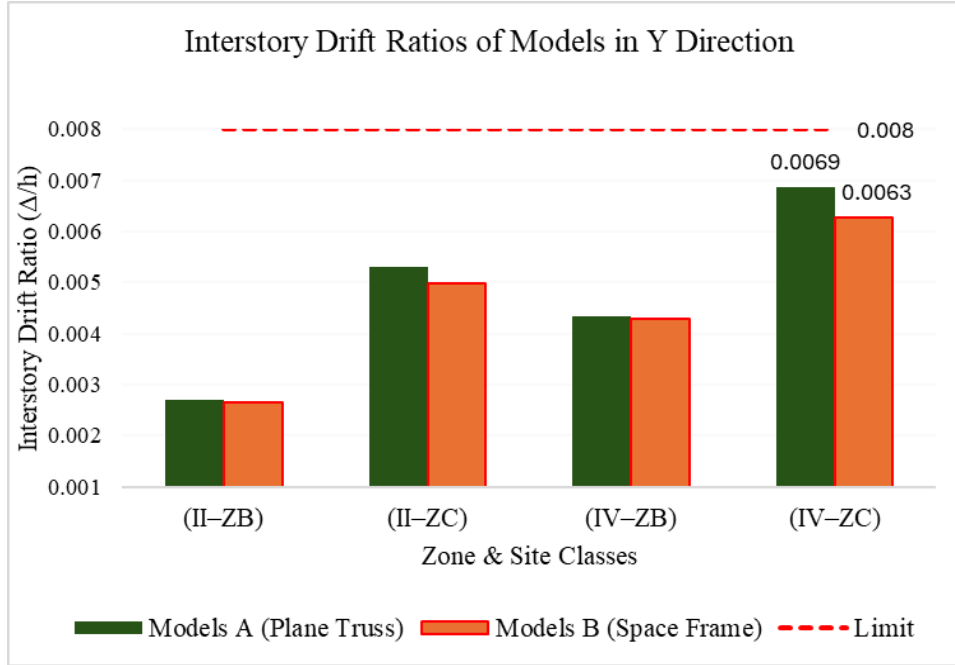


Figure 3. Interstory drift ratios of Models A & B in Y direction

Wind-Induced Structural Response

Figure 4 shows the lateral displacement values of columns under wind load for different models. Based on Chapter 15 of the SDCCSS–2016 regulation, the calculated displacement for all models is less than the permissible limit of $h/150$ (20 mm). The results show that all models under wind load are within the acceptable range for performance and occupant comfort. None of the columns exceeds the permissible displacement limit.

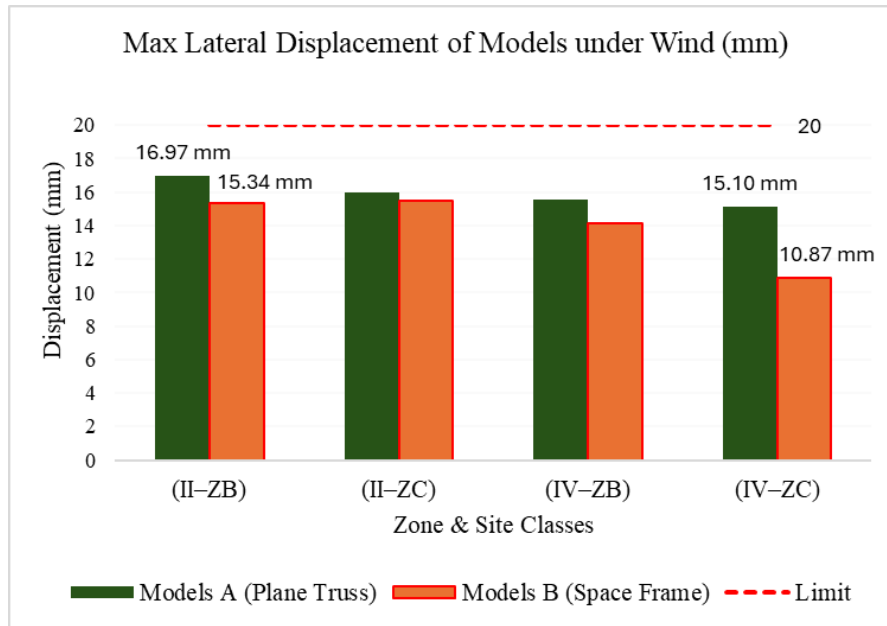


Figure 4. Wind-induced lateral displacement of Models A & B in Y-direction

Using the data in Table 7 and Equation 2 to examine the effect of structure type, we calculated the percentage reduction in lateral displacement when changing from model A to model B, which is:

$$\% \text{ Reduction} = \frac{\delta_A - \delta_B}{\delta_A} \times 100 \quad (3)$$

The results, reported in Table 7, show significant effects on displacement reduction from changes in structure type, climate region, and site class.

Table 7. Percentage reduction in lateral displacement when switching from Plane Truss (Model A) to Space Frame (Model B) under wind load

Zone & Site Classes	% Reduction A → B
II-ZB	9.6%
II-ZC	3.0%
IV-ZB	8.9%
IV-ZC	28.0%

Effect of Climatic Regions on Structural Performance

As shown in Figures 5 and 6, in both models A and B, for cases A2 and B2, the wind-induced displacement is larger than the earthquake-induced displacement and controls the structural behavior due to the relatively high wind pressure in zone II ($q_p = 1.08 \text{ kN/m}^2$). In contrast, in models A4 and B4, despite the wind pressure decreasing to 0.51 kN/m^2 in zone IV, the increase in seismic force intensity has led the earthquake-induced displacement (about 18.42 mm) to dominate as the critical design case. However, the displacement values in all models remain within the permissible limits set by the regulations.

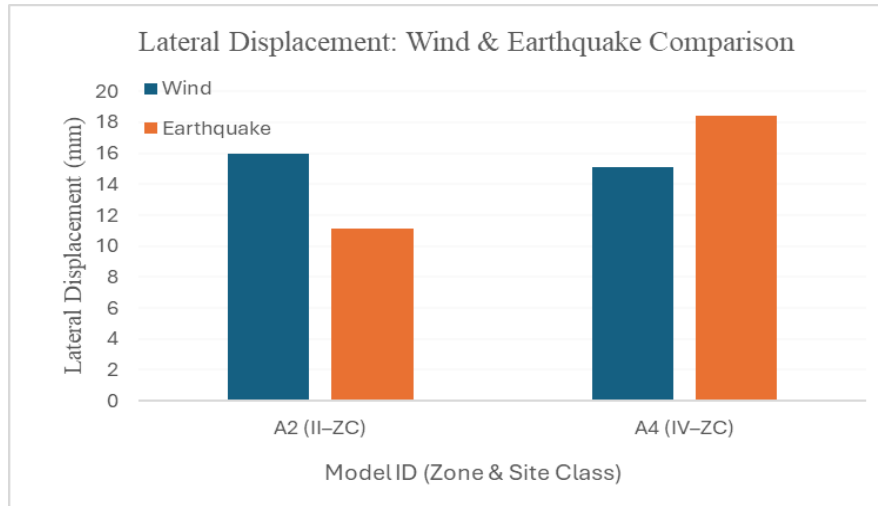


Figure 5. Comparison of wind and earthquake displacements for A2 and A4 models

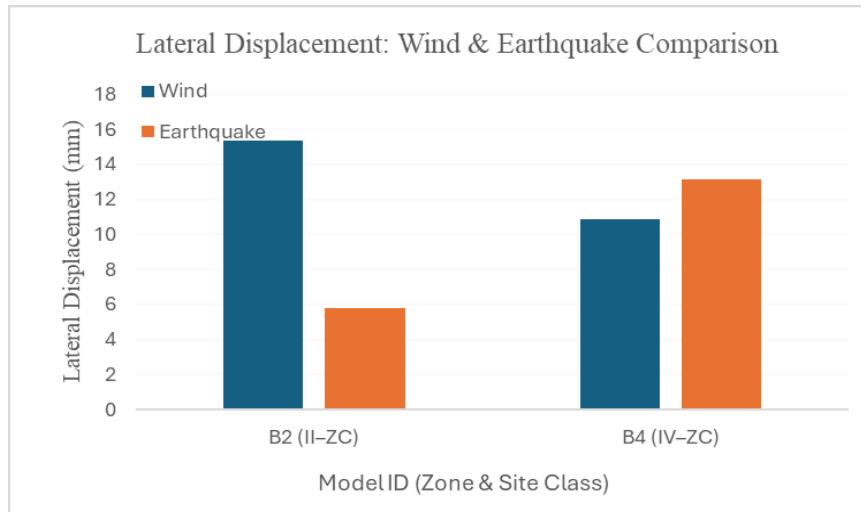


Figure 6. Comparison of wind and earthquake displacements for B2 and B4 model

Weight Comparison of Structural Models

Looking at the results extracted from the total weight of the models, a significant technical and economic advantage is seen in the B-type configurations; so that replacing the plate truss system (Model A) with a space frame (Model B) in all scenarios has led to a significant weight reduction of about 30%. For example, while Model A1 weighs 56.48 tons, Model B1, with the same application and dimensions, weighs only 39.67 tons. This significant weight difference, together with the earlier drift results, shows that the space frame system, due to its three-dimensional behavior, not only provides higher lateral stiffness but also greatly reduces steel consumption by optimally distributing forces within the members. Also, the relative stability of weight in all four climatic and seismic zones (A1 to A4) indicates that the design of sections in these mid-rise structures was mostly influenced by combinations of gravity loads and minimum regulatory requirements, and changes in seismic and wind parameters did not cause severe fluctuations in the total weight of the structure. A comparison of the total structural steel weight (tons) between the flat truss (Model A) and space frame (Model B) configurations is shown in Figure 7. The weights and percentage reduction are also shown in Table 8.

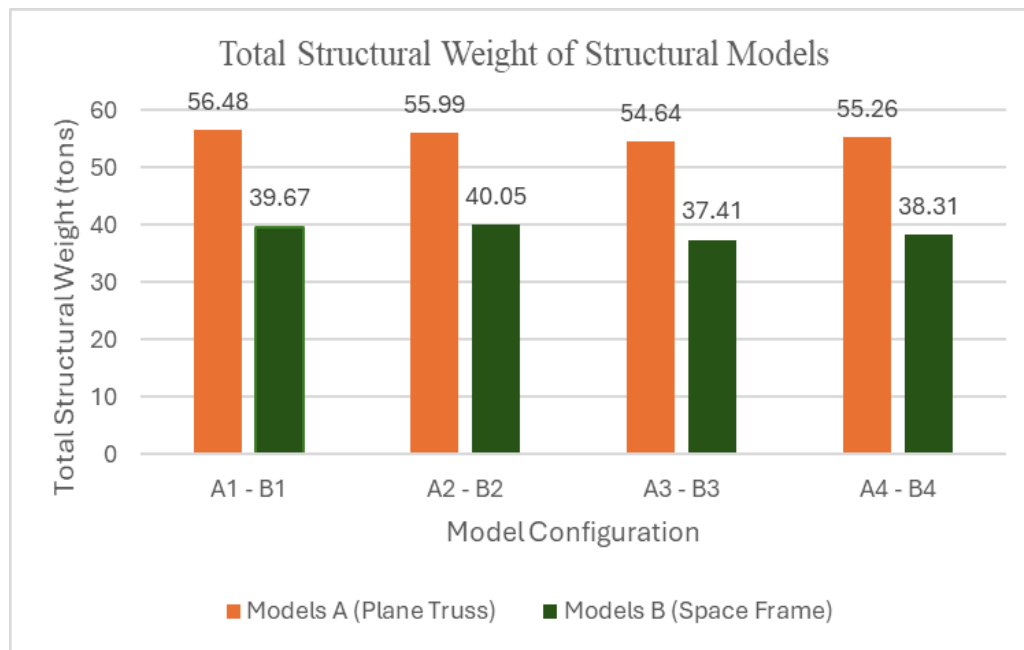


Figure 7. Comparison of total structural steel weight (tons) between Plane Truss (Model A) and Space Frame (Model B) configurations.

Table 8. Plane truss vs. Space frame: Weights and reduction percentages

Model ID	Plane Truss (A) (ton)	Space Frame (B) (ton)	Weight Reduction (%)
A1-B1	56.48	39.67	29.77%
A2-B2	55.99	40.05	28.47%
A3-B3	54.64	37.41	31.53%
A4-B4	55.26	38.31	1.04

Conclusion

In this study, the behavior of two structural systems, plate truss (Model A) and space frame (Model B), under wind and earthquake loads, was investigated under different conditions. The lateral displacement of all models under wind and earthquake loads was less than the code limit. Comparison of the models showed that the space frame performs better at controlling lateral displacement and, in some cases, achieves a significant reduction compared to the plate truss. Also, regional conditions showed a clear effect on the results. In region II, due to higher wind pressure, the wind effect was shown to be dominant in the models, while in region IV, with decreasing wind pressure and increasing earthquake effect, the seismic load plays a more decisive role. On the other hand, the soil type (site classes ZB and ZC) also affects the displacement and, in some cases, especially in the space frame model, reduces it. Overall, the results show that the choice of structural system and consideration of regional conditions can significantly affect the structure's behavior and displacement.

Recommendations

According to the results of this study, it is recommended to use a space frame system due to its performance in controlling lateral displacement, especially under wind loading conditions. Moreover, in designing structures, it is very significant to take into consideration the regional conditions and the classification of the soil, since these factors can affect structural behavior. As recommendations for future studies, it is suggested that the impact of other factors, such as the height of the structure, geometric irregularities, and nonlinear behavior, should be further investigated in order to have a more comprehensive understanding of the structural behavior.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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Author(s) Information

Siamak Aghaei

Yıldız Teknik University, Department of Civil Engineering,
İstanbul, Türkiye
ORCID iD: <https://orcid.org/0000-0002-5796-9280>

Ali Koken

Konya Technical University, Department of Civil
Engineering, Konya, Türkiye
ORCID iD: <https://orcid.org/0000-0002-2461-132X>
Contact e-mail: akoken@ktun.edu.tr

*Corresponding author(s) contact email

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Comparative Analysis of Clustering Algorithms for Meteorological Regime Characterization Over Türkiye Using ERA5 Reanalysis Data

Ali Utku Akar

Konya Technical University

Cevat Inal

Konya Technical University

Abstract: Precise analysis and region-specific classification of meteorological parameters constitute a critical prerequisite for advanced scientific processes, ranging from artificial intelligence modeling to complex atmospheric research. The multidimensional and inherently volatile nature of these parameters often hinders the extraction of latent patterns through conventional statistical methods. At this juncture, clustering analysis facilitates the derivation of optimized analytical domains by automatically classifying data points with shared climatological signatures. This study adopts a comparative perspective by evaluating data-driven (K-means and K-medoids), spatial-based (Spatially Constrained Multivariate Clustering: SCMC), and density-based (DBSCAN) clustering approaches to reveal regional variability and spatial dependency across Türkiye. The primary motivation of this research is to determine which approach reflects the heterogeneous structure with high representational power across diverse topographical settings, thereby establishing an optimal clustering strategy for atmospheric modeling. This study aims to characterize and regionally decompose Türkiye's meteorological profile by leveraging high-resolution European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 reanalysis parameters, including temperature, pressure, relative humidity, instantaneous moisture flux, geopotential, 2m temperature and dewpoint temperature. Methodologically, the ERA5 were downscaled to the geographical coordinates of meteorological stations via point-based extraction and validated against in-situ observations provided by the Turkish State Meteorological Service. Performance analyses indicate that the SCMC approach achieved the highest precision in delineating meteorological similarities and disparities. The comparative success ranking was established as SCMC>DBSCAN>K-medoids>K-means. Findings demonstrate that while K-means and K-medoids are effective in identifying broad climatic zones, the SCMC algorithm generates significantly more consistent and spatially continuous clusters. Furthermore, DBSCAN successfully isolated microclimatic regions with extreme values, such as the Eastern Black Sea, from the primary clusters. Consequently, this research demonstrates that integrating high-resolution reanalysis data with advanced spatial clustering techniques provides a more precise and dynamic decision-support mechanism for regional meteorological analysis and environmental planning compared to conventional methodologies.

Keywords: ERA5 reanalysis data, Clustering analysis, Meteorological research

Introduction

The global climate system is a dynamic structure shaped by the complex interactions of atmospheric circulation, ocean currents, and thermodynamic processes (Bridgman & Oliver, 2014). Over the last seven decades, accelerating anthropogenic impacts have disrupted this natural balance, making “global warming” and the resulting “climate change” the most significant environmental threat facing humanity (Khan, 2024). Understanding the local and regional effects of climate change requires not only tracking temperature increases but also clearly partitioning how meteorological regimes evolve both temporally and spatially (Xie et al., 2015).

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The high dimensionality and non-linear nature of meteorological data can render traditional statistical methods insufficient in explaining such complexity (Singh et al., 2024). At this juncture, clustering analysis, a prominent machine learning and data mining technique, emerges as a critical tool for identifying hidden patterns within vast datasets and defining sub-regions or regimes with similar characteristic features (Morawiec et al., 2026). Observations located within the same cluster exhibit a higher degree of similarity to one another based on a specific criterion compared to observations in other clusters. The fundamental principle is to establish a structure where intra-group variation is minimized while inter-group variation is maximized. The origins of clustering analysis date back to the anthropological studies of Driver and Kroeber (1932) and were later adapted to psychology. Cattell (1943) utilized this method extensively for trait theory classifications in personality psychology. As a core step of exploratory data analysis, this method is frequently employed in statistical data processing (Everitt et al., 2011). It holds a significant place in various scientific and engineering fields, such as medicine and health sciences, economics and finance, information technology, telecommunications, and machine learning.

Clustering analysis is generally implemented in four stages: constructing the data matrix, calculating similarity or distance matrices, determining the clustering methods to be employed, and interpreting the obtained results. The construction of the data matrix constitutes the initial phase of the analysis. Primarily, observation values for n units across p variables are obtained from populations for which no definitive information regarding natural classifications exists (Anderberg, 2014). During the selection of variables for the research, the theoretical and practical aspects of the subject must be considered, and the current literature should be reviewed. Like other multivariate statistical methods, clustering analysis does not possess the capability to rectify errors made during the variable selection stage. Furthermore, extreme outliers—observations that deviate significantly from the general trend—must be identified at this stage. In the second phase of the analysis, similarity or distance matrices are calculated (Everitt et al., 2011). In the third stage, the most appropriate method among existing techniques is selected, and clusters are generated. The fourth and final stage involves the interpretation of the results. In determining the correct number of clusters and evaluating the suitability of the structure, clusters consisting of only one or two observations should be viewed with caution. Care should be taken to ensure that the variables used in clustering exhibit significant differences between clusters. Additionally, it is essential that the results are theoretically valid and consistent with the existing literature (Kaufman & Rousseeuw, 2009). The methodology of clustering analysis offers a wide variety of techniques depending on the objective of the study and the structure of the data. Traditionally, these are categorized into two main groups: hierarchical techniques, based on the presentation of results, and non-hierarchical techniques, which partition the dataset according to a pre-determined number of clusters (Silahtaroglu, 2013). Recently, location-based techniques that establish relationships between data attributes and geographic coordinates have gained critical importance in both academic and practical applications. Through statistics such as spatial autocorrelation, these approaches enable the identification of regional differences by determining the clustering patterns of areas with high, low, or outlier values for any given variable in the dataset (Şişman, 2021).

Clearly revealing spatial variability is of vital importance for developing “regional and specific” strategies rather than “one-size-fits-all” solutions in the fight against climate change. For instance, while drought regimes become dominant in one region, the intensification of extreme precipitation regimes in a neighboring area necessitates distinct adaptation policies for each. This study aims to emphasize the methodological power of clustering analysis in partitioning meteorological regimes and to discuss the role of the precise spatial data provided by these analyses in creating climate-resilient cities and sustainable ecosystems. By evaluating data-driven (K-means and K-medoids), spatial-based (Spatially Constrained Multivariate Clustering: SCMC), and density-based (Density-Based Spatial Clustering of Applications with Noise: DBSCAN) clustering approaches, this study aimed to reveal regional variability and spatial dependency across Türkiye from a comparative perspective. In this context, Türkiye’s meteorological profile was characterized and regionally decomposed by leveraging high-resolution ERA5 reanalysis parameters from the European Centre for Medium-Range Weather Forecasts (ECMWF), including temperature, pressure, relative humidity, instantaneous moisture flux, geopotential, 2m temperature, and dewpoint temperature.

Method

Study Area

The study area encompasses a wide geography across Türkiye, selected to represent the region’s diverse geoclimatic conditions (Figure 1). Türkiye exhibits significant climatic complexity due to its unique geographical position as a bridge between Europe and Asia, surrounded by three distinct seas. This diversity

ranges from temperate Mediterranean and Aegean maritime climates—characterized by high humidity and substantial precipitable water vapor—to semi-arid and continental conditions in Central and Eastern Anatolia, where pronounced temperature gradients and strong seasonal variability are observed. Furthermore, the complex topography, including the North Anatolian and Taurus mountains ranges, generates distinct microclimates and pronounced orographic effects that significantly influence atmospheric delay and signal propagation. Overall, this multifaceted meteorological environment provides an ideal natural laboratory for evaluating the performance and robustness of cluster-based models under varying atmospheric regimes and pressure–temperature profiles.

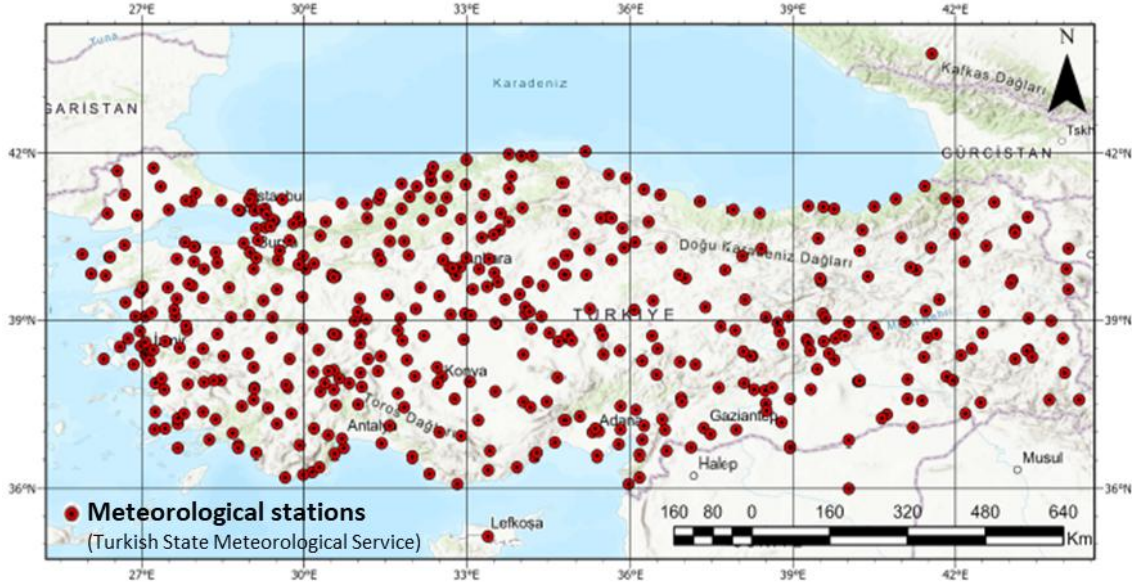


Figure 1. Study area and spatial distribution of meteorological stations

Data Acquisition and Processing

ERA5 reanalysis data is used in this study. Meteorological parameters extracted from ERA5 serve as the basis for the clustering analysis, enabling the identification of spatial regimes within the study area. Figure 2 shows the monthly mean maps of meteorological parameters, covering the five-year period from 2020 to 2024. Here, *pressure (P)* represents the pressure force per unit area exerted on land, ocean, or inland water surfaces. *2m temperature (T2m)* denotes the air temperature at 2 m above the surface, while *2m dewpoint temperature (DT2m)* represents the dew point temperature at the same height and serves as an indicator of atmospheric humidity. *Geopotential (GEO)* refers to the gravitational potential energy per unit mass at a specific location relative to mean sea level, representing the work required to raise a unit mass against gravity. *Temperature (T)* describes atmospheric temperature available at multiple pressure levels along the vertical profile. *Relative humidity (RH)* quantifies the water vapor mass per kilogram of moist air, where moist air consists of dry air, water vapor, cloud liquid water, cloud ice, rain, and falling snow. Finally, *instantaneous moisture flux (IMF)* is defined as the net moisture exchange rate between the surface and the atmosphere, resulting from evapotranspiration and condensation processes over a given timeframe.

K-Means Clustering

K-means clustering is one of the most fundamental and widely used methods in unsupervised learning. The primary objective of this algorithm is to partition a dataset consisting of n data points into a pre-determined number of k clusters, thereby maximizing intra-cluster similarity and minimizing inter-cluster differences. As a centroid-based algorithm, each cluster is defined by a cluster center (μ_i) representing the average position of the points within that cluster (Aldino et al., 2021). The process operates through an iterative cycle starting from k randomly selected initial centers and consists of two main steps: assignment and update. During the assignment step, each data point x_i is assigned to the nearest center μ_i , typically using Euclidean distance as the proximity metric. In the update step, the new center of each cluster is recalculated by taking the arithmetic mean of all data points assigned to that cluster, which ensures the repositioning of centers to provide the minimum Within-Cluster Sum of Squares (WCSS) (Kriegel et al., 2017).

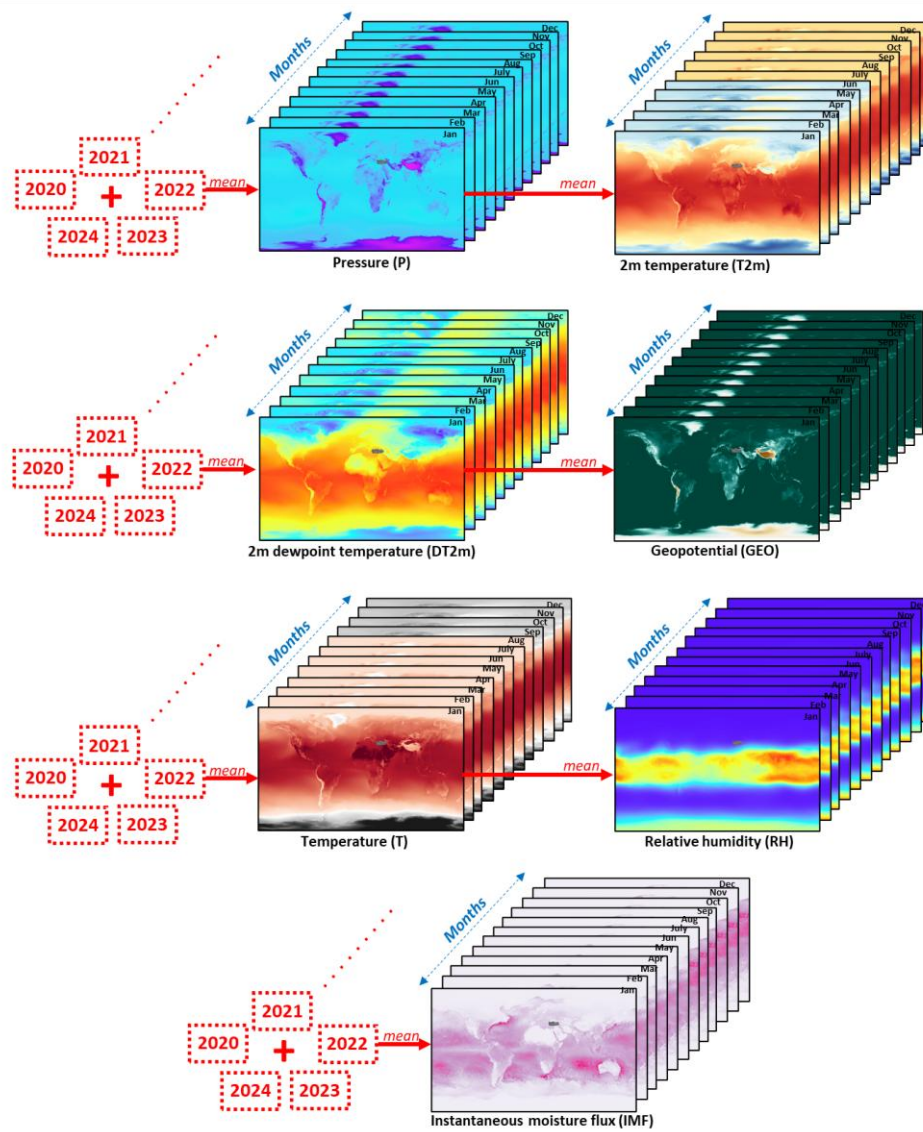


Figure 2. Monthly means spatial distributions derived from meteorological parameters extracted from the ERA5 reanalysis dataset

One of the greatest challenges of the algorithm is determining the optimum number of clusters (k). To make this selection and evaluate clustering quality, several methods are utilized, including the Elbow method, Silhouette analysis, Gap statistics, the Davies–Bouldin index, and the Calinski-Harabasz index. Furthermore, the Rand index and the Adjusted Rand index, which are correct for chance groupings, are employed to measure the agreement between two different clustering results.

K-Medoids Clustering

K-medoids is an unsupervised learning and data clustering method similar to the K-means approach. However, unlike K-means, the K-medoids algorithm selects cluster centers from actual observations within the cluster (medoids) rather than using averages. This feature makes K-medoids particularly robust against outliers and noise (Lund et al., 2021). The fundamental basis of K-medoids clustering is to find k clusters among n observations by first identifying a random representative observation for each cluster. Each remaining observation is then assigned to the medoid to which it is most similar. Instead of taking the average value of the observations in each cluster, K-medoids utilizes these representative observations as reference points (Kaur et al., 2014). The approach takes the input parameter k , which represents the number of clusters to be partitioned among the set of n observations, from the user. It operates based on the principle of minimizing the sum of dissimilarities between each observation and its corresponding reference point. This process is executed using the following equation (1):

$$\sum_{i=1}^k \sum_{x_j \in S_i} d(x_j, m_i) \quad (1)$$

Spatial-Based Clustering

While most clustering methods consider the similarities between observations or variables in a dataset, they often neglect location information, leading to clusters formed without regard for geographic or spatial relationships. To address this limitation, SCMC has been developed as an approach that incorporates both spatial and non-spatial attributes into the analysis. Based on the Spatial ‘K’luster Analysis by Tree Edge Removal (SKATER) algorithm, SCMC is considered an unsupervised machine learning technique because it does not require pre-classified features or training data to identify natural patterns in the data. The process assumes a network structure of nodes and edges, aiming to connect nodes with the lowest possible cost through a Minimum Spanning Tree (MST) algorithm. To restrict cluster membership to contiguous or nearby features, the method first establishes a connectivity graph representing spatial relationships. From this graph, an MST is designed to summarize both spatial relationships and data similarity, where each edge weight is proportional to the similarity of the connected objects. While various algorithms like Kruskal (1956) or Boruvka can be used, the approach proposed by Assunção (2006) typically utilizes the Prim algorithm. Once the MST is constructed, the tree is pruned by removing specific branches to create separate clusters. This pruning process selects edges that minimize internal cluster diversity while avoiding single-feature clusters. Although the algorithm optimizes cluster similarity at each iteration, there is no guarantee that the final result will be globally optimal (Pettie & Ramachandran, 2002).

Density-Based Clustering

DBSCAN is a powerful unsupervised machine learning algorithm that focuses on the density distribution of points within a dataset and does not require the number of clusters to be predefined. Unlike traditional centroid-based algorithms, DBSCAN categorizes data into “core points”, “border points” and “noise” (outliers), allowing it to successfully identify clusters of arbitrary shapes. The performance of the algorithm primarily depends on two hyper-parameters: the radius distance (ϵ), which defines a point’s neighborhood, and the minimum number of points (**MinPts**) required to form a cluster within that radius. During the execution of the algorithm, if the number of points within the ϵ -neighborhood of a point is equal to or greater than **MinPts**, that point is defined as a core point and a new cluster is initiated. All core points that are density-reachable are merged into the same cluster, while low-density points that cannot be assigned to any dense region are labeled as “noise” and excluded from the clusters. This feature makes DBSCAN particularly effective in complex datasets containing outliers and non-linear spatial structures.

Results and Discussion

Clustering algorithms with different functional principles were employed to group meteorological data and identify regional similarities/differences. Following the acquisition of station-scale datasets from ERA5, K-means, K-medoids, SCMC and DBSCAN were applied. Seven parameters related to climatic characteristics (T, GEO, P, IMF, RH, T2m, and DT2m) were utilized as input variables for the clustering analysis and subsequently evaluated statistically. All analyses were conducted using Python (v3.12.7, Spyder 5), IBM SPSS Statistics, and ArcGIS Pro.

K-Means Clustering Results

To determine the optimal number of clusters (k) for K-means analysis, the Elbow Method was employed by calculating the WCSS for each k value. The analysis identified two potential inflection points at $k=4$ and $k=10$. While $k=4$ provided a simplified model representing the fundamental structure of the dataset, $k=10$ allowed for a more granular decomposition of sub-segments and small-scale variations. Due to the complex and heterogeneous nature of the meteorological data, $k=10$ was selected as the final cluster count to achieve higher precision. Following the optimization of all parameters, the final clustering was executed to delineate regional patterns across Türkiye (Figure 3).

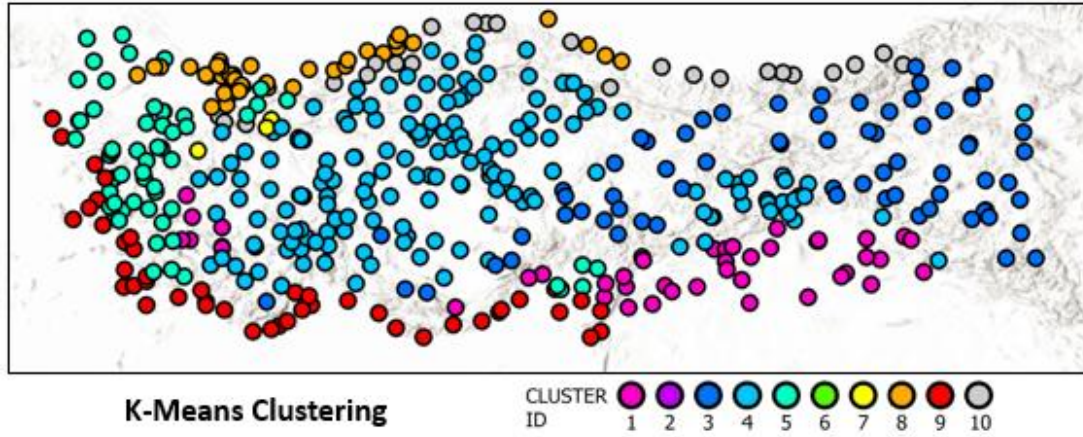


Figure 3. Cluster groups formed as a result of the K-means application

While the clusters diverge at specific locations, the spatial separation may not appear fully distinct. This is primarily because the method is applied directly to the numerical dataset; although stations with similar meteorological characteristics are grouped together, their explicit spatial weights and geographical relationships are not fully integrated into the algorithm. As seen in Figure 3, cluster distributions emerge from the coastal regions toward the interior.

To identify cluster groups with varying meteorological values in Türkiye through statistical analysis, box plots were generated. The relationship between monthly meteorological data belonging to these clusters was evaluated via descriptive statistics. In the box plots, colors represent the respective cluster groups (Figure 4). Minimum, maximum, mean, quartiles, and outliers were analyzed, and overlapping box plots were identified as similar clusters. This process was performed separately for each month and parameter. The meteorological parameters were processed using IBM SPSS Statistics to determine their significance levels, which are indicated by the below Table 1.

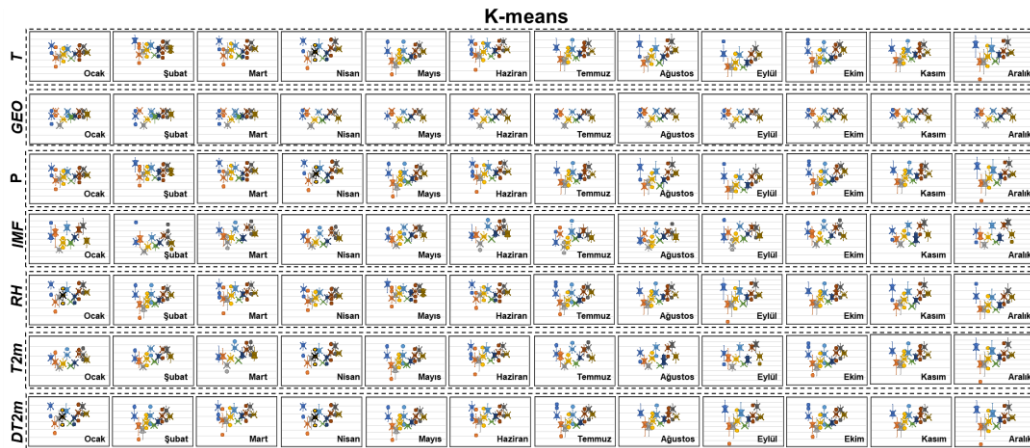


Figure 4. Box plots created based on monthly parameters in cluster groups determined by K-means

Table 1. Identifying clusters that are similar to each other among the clusters obtained from K-means

Cluster	1	3	4	5	7	8	9	10
T								
GEO								
P								
IMF								
RH								
T2m								
DT2m								
	1	2	2	4	2	4	3	1

Based on the black-filled cells in Table 1, it is observed that Clusters 5 and 8 exhibit the highest frequency of shared meteorological parameters across all evaluations. This indicates that these two identified cluster groups possess closely aligned data characteristics. Conversely, no significant similarities or correlations were found among the parameters of Clusters 1, 3, 4, 7 and 10.

3K-Medoids Clustering Results

The Silhouette Method was employed to determine the optimal number of clusters (k) for the K-medoids algorithm. As the silhouette coefficient evaluates both the cohesion of an observation within its own cluster and its separation from neighboring clusters, it provides a robust validity metric aligned with the K-medoids approach. The most meaningful cluster count for the dataset was identified by comparing the average silhouette scores calculated for various k values.

Analysis of the silhouette scores revealed that the linear upward trend in the average score stabilized at ten clusters; consequently, $k=10$ was selected as the optimal value. Generally, an average silhouette width exceeding 0.7 is considered indicative of a “strong” clustering structure, while values between 0.5 and 0.7 are deemed “reasonable”, and those between 0.25 and 0.5 are classified as “weak”. In the scenario where $k=10$, the silhouette width exceeded the 0.7 threshold, confirming that the K-medoids clustering provides a highly robust and well-defined representation of the data.

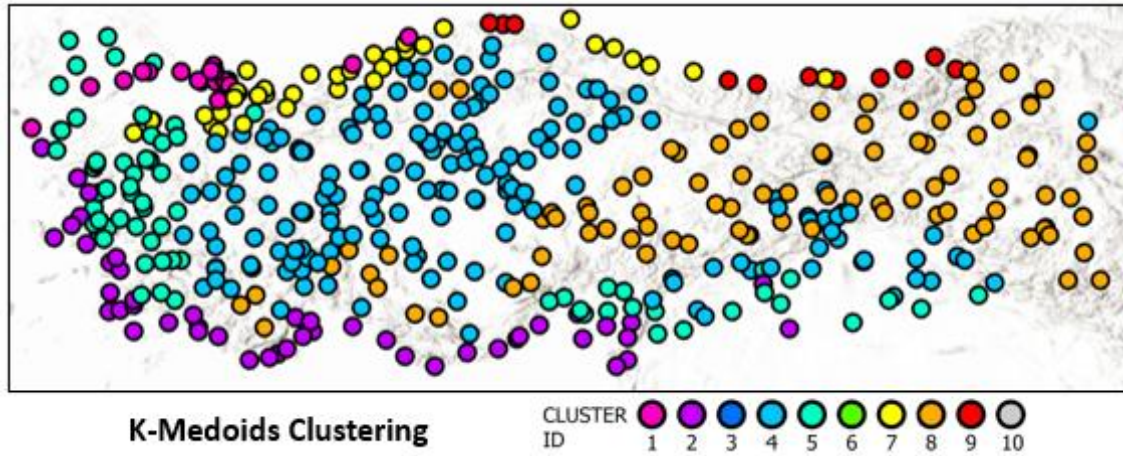


Figure 5. Cluster groups formed as a result of the K-medoids application

Figure 5 illustrates the clustering map resulting from the K-medoids application. While Clusters 4 and 8 correspond to the regions of Türkiye characterized by a terrestrial climate, Clusters 1, 2, 5, 7, and 9 exhibit a distinct separation toward the coastal areas, driven by the influence of RH and the IMF. The box plots generated for the statistical identification of cluster groups with similar or divergent meteorological values in Türkiye are presented in Figure 6. The corresponding data derived from this analysis are summarized in Table 2.

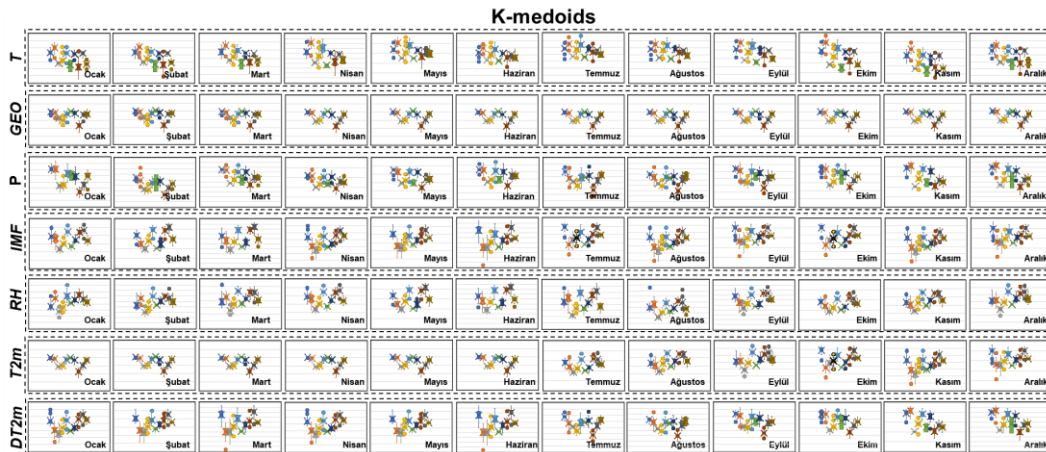


Figure 6. Box plots created based on monthly parameters in cluster groups determined by K-medoids

Table 2. Identifying clusters that are similar to each other among the clusters obtained from K-medoids

Cluster	1	2	4	5	7	8	9
T							
GEO							
P							
IMF							
RH							
T2m							
DT2m							
	4	3	1	7	5	0	1

Based on the results presented in Table 2, clusters identified as meteorologically similar in K-means were observed to diverge in the K-medoids application. The fundamental difference between these two algorithms stems from their sensitivity to outliers: while K-means determines cluster centers based on the mean value, K-medoids selects an actual data point within the cluster as the center (the medoid), making it more robust against outliers. Specifically, while Clusters 5 and 8 were identified as the most similar in K-means, Clusters 5 and 7 emerged as the groups containing the most common parameters in the K-medoids analysis.

SCMC Results

Clusters were generated via ArcGIS Pro under spatial constraints, accounting for both geographical location and multivariate characteristics. In contrast to the previously mentioned clustering methods, the initial number of clusters for SCMC was set to 10; subsequently, optimization parameters—such as cluster size constraints (number of clusters), spatial constraints (trimmed delaunay triangulation), and membership probabilities—were utilized to achieve the most effective differentiation among these ten clusters.

The clustering map derived from the SCMC analysis is presented in Figure 7. Distinct spatial boundaries are observed between the clusters in Türkiye, particularly for Clusters 2, 4, 5, 7, 8, 9, and 10. This indicates that climate, topography, and spatial factors exert a strong influence on the formation of these clusters.

It is evident that SCMC serves as a significant method for clustering geographical and climatic parameters. Furthermore, it can be utilized as a strategic guide in geography-based decision-making processes; however, the cluster parameters must be statistically examined. To this end, an approach was adopted where spatial and non-spatial characteristics were handled holistically. Based on the box plots presented in Figure 8, similar clusters were identified and marked in Table 3.

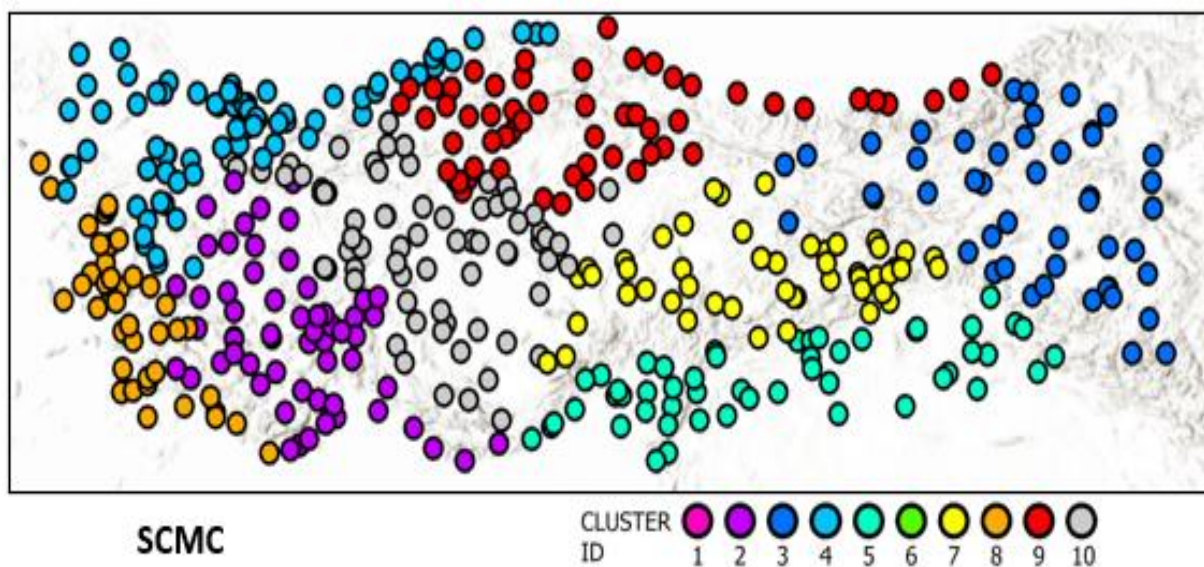


Figure 7. Cluster groups formed as a result of the SCMC

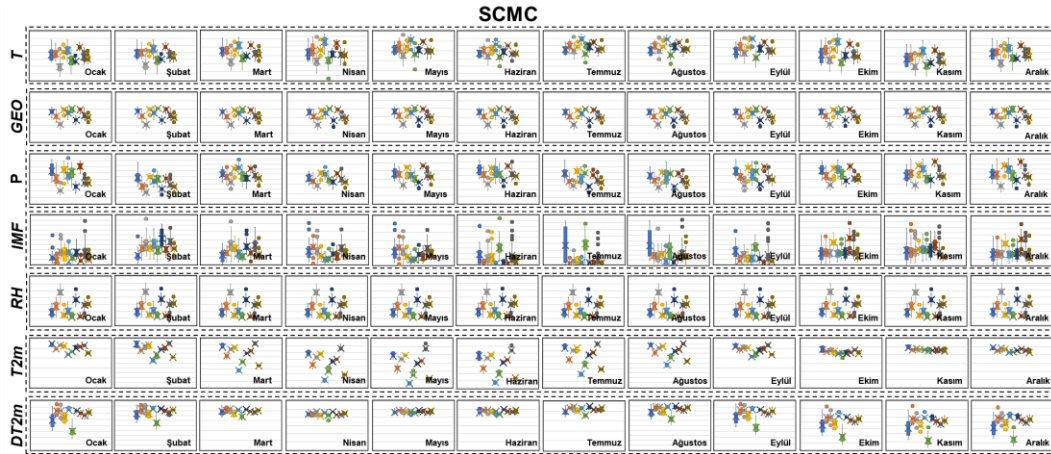


Figure 8. Box plots created based on monthly parameters in cluster groups determined by SMC algorithm

Table 3. Identifying clusters that are similar to each other among the clusters obtained from SMC

Cluster	2	3	4	5	7	8	9	10
T								
GEO								
P								
IMF								
RH								
T2m								
DT2m								
	3	1	7	2	0	0	1	0

Based on the results derived from Table 3, it is observed that Clusters 2 and 4 are characteristically very similar. Evaluating the T, GEO, P, IMF, RH, T2m, and DT2m parameters on a monthly basis reveals that these variables overlap for Clusters 2 and 4 across almost all months.

DBSCAN Clustering Results

In this study, the maximum search distance (ϵ) and the minimum number of features required per cluster were determined through an iterative optimization process. Cluster memberships were identified based on these density criteria. When the minimum feature requirement per cluster is low (15), the differentiation of meteorological data is poorer, resulting in fewer clusters. In other words, due to the lenient density criteria, the algorithm is likely to merge most stations under a single cluster. Conversely, a higher minimum feature count (45) implies a requirement for stronger similarity among station data, leading to more refined cluster separation. Consequently, a scenario with a minimum point count of “45”, a cluster count of “8”, and a search distance of “150” was selected.

The clustering map generated using the selected parameters in the DBSCAN algorithm is presented in Figure 9. Unlike other clustering methods, noisy data were excluded from the map in the DBSCAN analysis. These noisy data represent stations that could not be assigned to any specific cluster due to their failure to meet the required DBSCAN criteria, specifically the search distance (ϵ) and the minimum number of features per cluster (*MinPts*). Based on the box plots presented in Figure 10, similar clusters were identified and marked in Table 4.

The comparative analysis of meteorological parameters across the identified clusters reveals a significant degree of similarity between Cluster 2 and Cluster 4. As illustrated in the parameter intersection matrix, Cluster 4 stands out as the most representative group, exhibiting commonalities across six out of seven evaluated parameters. Cluster 2 follows this trend by sharing three key parameters (T, IMF, and T2m) with the overall meteorological profile. The high frequency of black-filled cells for Cluster 4, particularly when compared with the overlap in Cluster 2, suggests that these two groups possess closely aligned climatic characteristics. While other clusters (such as 7 and 8) show no significant parameter intersections, the strong convergence in Clusters 2 and 4 indicates that the stations within these groups respond similarly to the multivariate atmospheric variables.

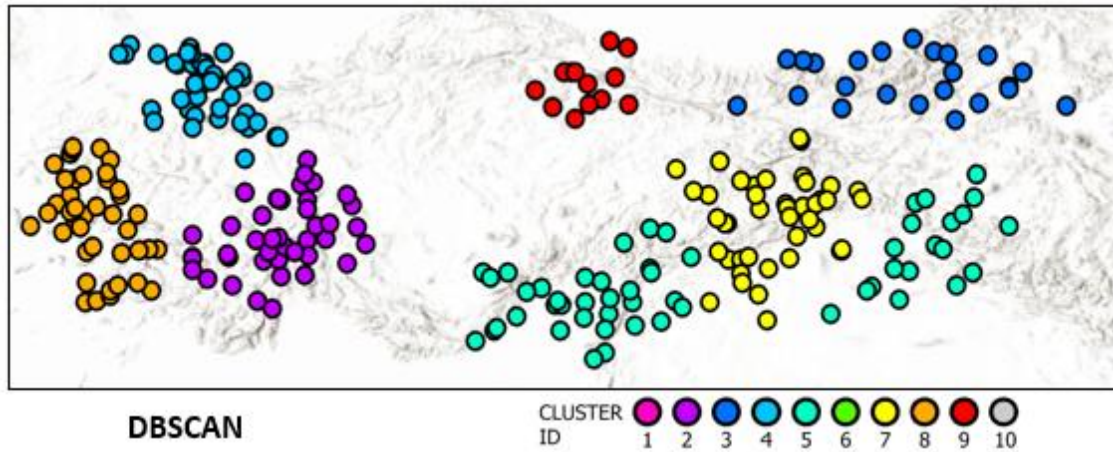


Figure 9. Cluster groups formed as a result of the DBSCAN

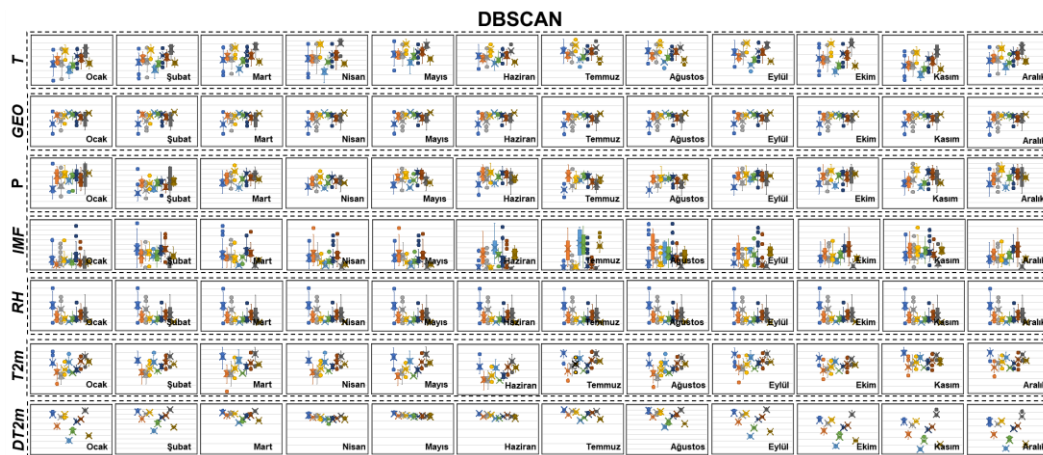


Figure 10. Box plots created based on monthly parameters in cluster groups determined by DBSCAN

Table 4. Identifying clusters that are similar to each other among the clusters obtained from DBSCAN

Cluster	2	3	4	5	6	7	8	9
T								
GEO								
P								
IMF								
RH								
T2m								
DT2m								
	↓	↓	↓	↓	↓	↓	↓	↓
	3	1	6	1	0	0	0	1

Overall Assessment of Clustering Algorithm Results

The similarities and divergences between cluster groups have been statistically established using K-means, K-medoids, SCMC, and DBSCAN approaches. However, it has not yet been determined which method most accurately reflects the characteristic meteorological regions. Specifically, the question of which algorithm best captures meteorological diversity remains to be addressed. To identify the most successful method in this regard, the following evaluative step was implemented.

A “cluster error” was assigned to each cluster across all clustering methods. First, the annual mean values were calculated by averaging the twelve-month meteorological data for each station within its respective cluster. This procedure was performed for all “n” stations in each cluster. Subsequently, the overall mean of these “n” stations was determined. The cluster score was obtained by calculating the residuals between the individual

meteorological values of each station and the determined cluster mean (Table 5). To eliminate discrepancies arising from the different units of the meteorological parameters, “Min-Max Normalization” was applied to the dataset.

Table 5. Comparison of clustering methods based on calculated cluster errors

Cluster No	K-means	K-medoids	SCMC	DBSCAN
Cluster-1	4.029	3.772	-	-
Cluster-2	-	3.579	3.126	3.508
Cluster-3	4.153	-	2.874	3.180
Cluster-4	4.165	4.100	2.554	2.777
Cluster-5	3.831	3.123	3.007	3.119
Cluster-6	-	-	-	3.112
Cluster-7	4.101	3.117	3.102	3.387
Cluster-8	3.765	3.869	2.664	2.899
Cluster-9	3.648	4.333	3.801	3.823
Cluster-10	4.235	-	3.455	-

Upon evaluating the cluster errors presented in Table 5, it is observed that the SCMC method yields relatively lower cluster errors compared to the other approaches. This indicates that SCMC provides the most robust representation of meteorological regionalization by minimizing intra-cluster variance. The results most closely aligned with those of the SCMC method were achieved by the DBSCAN algorithm, further validating the effectiveness of density-based and spatially constrained techniques in capturing complex climatic patterns. The comparative success of the algorithms is ordered as follows: SCMC > DBSCAN > K-medoids > K-means.

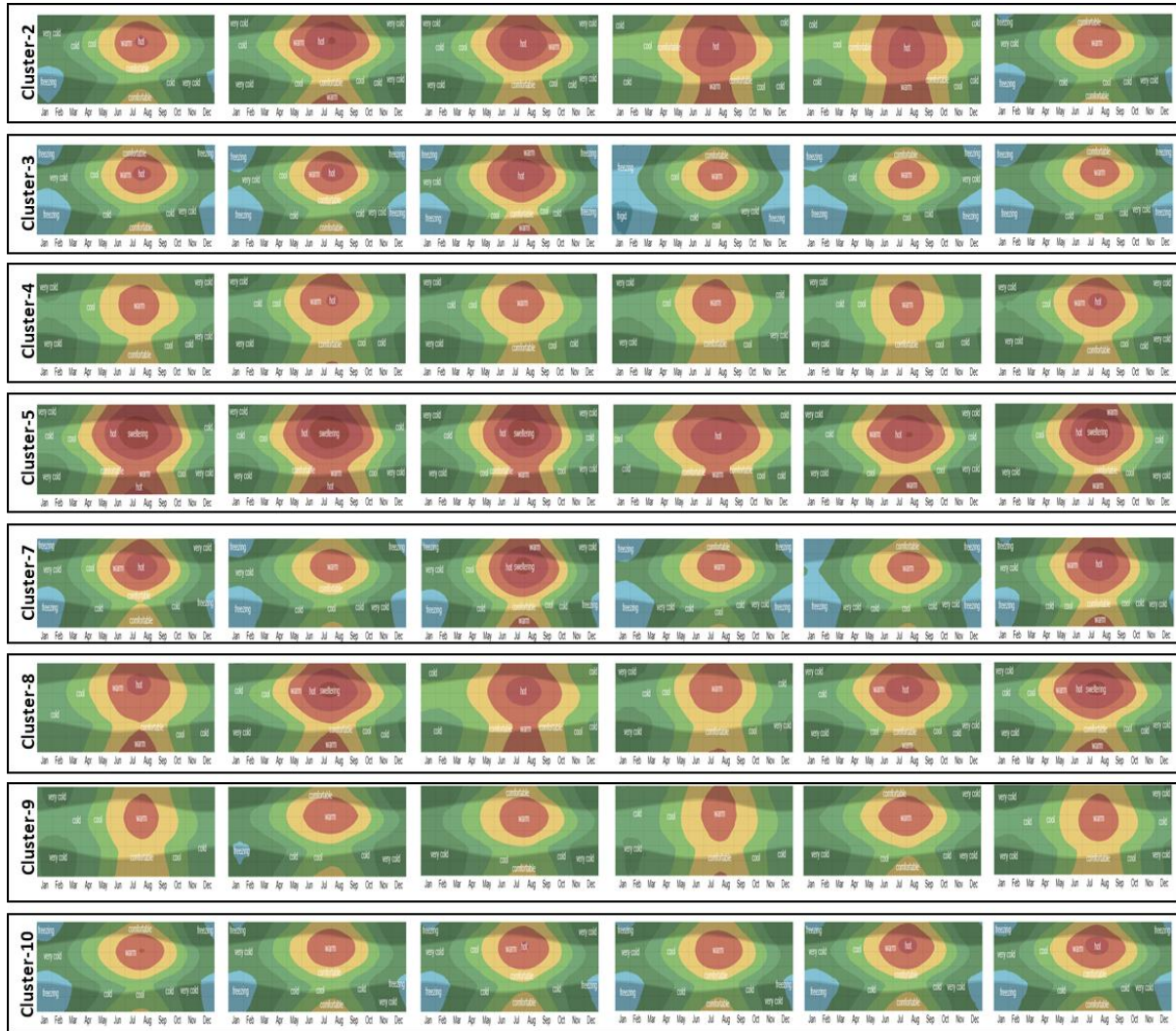


Figure 11. Monthly average temperature heat maps for randomly selected stations (Source: Weather Spark)

This ranking demonstrates that SCMC outperforms traditional methods by effectively integrating geographical constraints with climatic variables. While density-based approaches like DBSCAN follow closely due to their noise-filtering capabilities, partition-based algorithms such as K-means and K-medoids show relatively lower performance in capturing the complex, spatially-dependent structure of meteorological data.

Figure 11 presents the monthly variations of randomly selected stations within the clusters identified by the SCMC algorithm. This visual representation serves as a temporal validation of the clustering success. The analysis reveals two critical findings: high intra-cluster homogeneity and distinct inter-cluster heterogeneity. The temporal profiles in Figure 11 confirm that the SCMC algorithm effectively captures the climatic fingerprints of each region. The stations within the same cluster exhibit nearly identical seasonal patterns, particularly in the peak summer and winter months, indicating a high degree of internal consistency. For instance, the “hot/sweltering” core observed in Cluster-5 is consistently replicated across all sampled stations, while Cluster-3 maintains a dominant “freezing” signature. Furthermore, the inter-cluster variability is visually striking. The differences in the duration and intensity of thermal comfort zones between Cluster-2 and Cluster-10 underscore the high resolution of the SCMC method. The ability of the algorithm to group stations with such synchronized monthly transitions—despite their geographical distance in some cases—proves that the multi-variable and spatial constraint approach provides a superior regionalization compared to traditional methods.

Conclusion

The complex and dynamic nature of the global climate system necessitates advanced analytical approaches to accurately identify regional meteorological regimes. This study demonstrated the critical role of clustering analysis in decomposing the high-dimensional spatial and climatic characteristics of Türkiye, utilizing high-resolution ERA5 reanalysis data. By comparatively evaluating K-means, K-medoids, SCMC, and DBSCAN algorithms, the research highlighted the methodological strengths and limitations of distinct clustering techniques in spatial climatology. The comparative error analysis revealed that traditional partition-based algorithms, such as K-means and K-medoids, exhibit limited capacity in capturing the intricate spatial dependencies of meteorological variables. Because these algorithms primarily focus on the numerical similarities of the data while neglecting geographic proximity, their resulting clusters often lack spatial coherence. In contrast, the SCMC method yielded the lowest cluster errors and emerged as the most successful algorithm. By simultaneously optimizing for both attribute similarity and geographic contiguity, SCMC generated well-defined, robust, and homogenous climate zones. DBSCAN also demonstrated strong performance by effectively filtering out noisy data and identifying high-density regions without requiring a predefined number of clusters, making it the second most effective method in this comparative framework. Ultimately, integrating spatial data with advanced machine learning techniques bridges the gap between raw meteorological observation and actionable climate policy.

Recommendations

Based on the findings of this study, it is highly recommended to prioritize spatially constrained and density-based algorithms, such as SCMC and DBSCAN, over traditional partition-based methods like K-means when analyzing high-dimensional geoclimatic data. The high-resolution clustering maps generated through these advanced techniques should serve as a foundation for policymakers and urban planners to abandon “one-size-fits-all” approaches and instead develop region-specific climate adaptation strategies tailored to localized risks, such as interior drought or coastal extreme precipitation. Furthermore, future research should expand upon this framework by integrating spatiotemporal dynamics to track how these meteorological boundaries shift over time. Incorporating these baseline clusters into predictive machine learning models alongside Global Climate Models (GCMs), and expanding the input variables to include multidisciplinary environmental indices like NDVI and land use changes, will provide a more holistic and predictive understanding of the complex feedback loops between anthropogenic activities and regional climates.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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Author(s) Information

Ali Utku Akar

Res. Asst. (PhD)

Konya Technical University

Faculty of Engineering and Natural Sciences,

Department of Geomatics Engineering, Konya, Türkiye

ORCID iD: <https://orcid.org/0000-0001-5639-9987>

*Contact e-mail: auakar@ktun.edu.tr

Cevat Inal

Prof. Dr.

Konya Technical University

Faculty of Engineering and Natural Sciences,

Department of Geomatics Engineering, Konya, Türkiye

ORCID iD: <https://orcid.org/0000-0001-8980-2074>

*Corresponding author(s) email

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Power Supply Technologies for Collaborative Service Robots: Characteristics and Comparative Overview

Nina Valchkova

Bulgarian Academy of Sciences

Roman Zahariev

Bulgarian Academy of Sciences

Vasil Tsvetkov

Bulgarian Academy of Sciences

Yasen Paunski

Bulgarian Academy of Sciences

Georgi Angelov

Bulgarian Academy of Sciences

Abstract: The article examines the power supply of a Service Collaborative Robot, powered by a hydrogen fuel cell, intended for transporting seriously injured people and serving them in medical facilities. The qualities of this power supply are analyzed, highlighting its advantages in terms of environmental characteristics and its long "life" during the activities of serving patients in serious health conditions and transporting them to a hospital. Some main characteristics of this type of robot, powered by a hydrogen fuel cell, are analyzed, compared with robots powered by other types of power supplies, and its advantages when working in a hospital are shown.

Keywords: Service robot, Cobot, Hydrogen-powered robot.

Introduction

Power supply is a key element in the architecture of any mobile or stationary Collaborative Service Robot (Cobot) (CSR) (Kelly et al., 2021; Lynch et al., 2017). The duration of autonomous operation, functional capabilities and operational safety when interacting with people depend on its reliability, energy efficiency and safety (Miranda et al., 2025). An analysis of the state of the healthcare system justifies the increasing trend of creating robotic systems to assist medical personnel, especially after the development of the Covid 19 pandemic in recent years. When designing such a "cobot", a number of questions arise and it is important to answer them adequately. Creating such highly intelligent and "smart" robots is a difficult and extremely responsible task. In addition to the use of various sensors to provide information from the environment, on the basis of which a safe trajectory of movement of the robot itself and its manipulator is generated, management in the service process is carried out by recognizing voice commands, which is very important from the point of view of user convenience. The power supply system is of utmost importance for the long-lasting and trouble-free operation of the collaborative robot (Pa et al., 2016; Thounthong et al., 2009). The special requirements of these robots, designed to assist people with injuries or those in disadvantaged situations, in terms of the power supply system imply stable, uninterrupted and sufficiently long-term operation to fulfil the set goals. That is why it is necessary to develop and create power supply systems that, on the one hand, should be sufficiently compact and relatively light in weight, while at the

same time having the ability and being able to release enough energy necessary to perform the complex tasks set by the supervisor.

- In this sense of reasoning, it is particularly important to make a comparison of the characteristics of the existing power supply systems for the collaborative robot and especially to highlight the advantages of the hydrogen fuel cell power supply, which is gaining increasing popularity.
- The energy that hydrogen provides is sufficient and is an alternative to fossil fuels with the potential to achieve the goals for the development of society (Angelov, 2025). Hydrogen is found in many chemical compounds, such as water and organic biomass, and when burned, it releases heat energy – without pollutants or carbon dioxide. Increased energy consumption is a universal driver for improving the quality of life in all societies, from developing to developed countries. By supplying and using energy that improves the quality of life without endangering the environment, climate or geopolitical relations, the development effect is achieved. Hydrogen fuel cell technology is the subject of continuous research and development (Hasan et al., 2026). Hydrogen fuel cells are used as a clean and efficient alternative to traditional internal combustion engines, especially in the transport sector this sense of reasoning, it is particularly important to make a comparison of the characteristics of the existing power supply systems for the collaborative robot and especially to highlight the advantages of hydrogen fuel cell power supply, which is gaining increasing popularity (Ehsani et al, 2018).

Mobility Platform Analysis for Collaborative Mobile Robots

The mobility selection framework integrates quantitative and qualitative criteria using a multi-criteria decision-making (MCDM) approach. Key metrics include traction coefficient, ground pressure, energy consumption, obstacle negotiation capability, turning radius, and stability margin (Siciliano & Khatib, 2016). Advanced evaluation combines Analytical Hierarchy Process (AHP) for weighting and TOPSIS for ranking alternatives across diverse terrains and mission profiles.

Experimental Validation Framework

Experimental validation includes real-world tests and simulation-based evaluation. Metrics include traction force measurements, rollover stability, climbing angle, energy profiles under various terrains, and mobility autonomy. These tests validate theoretical models and guide optimization of hybrid systems.

Mathematical Models of Mobility Systems

Mathematical modeling includes kinematic equations, dynamic models, and energy consumption formulations. Differential drive equations, track-ground interaction models, and legged mobility gait models form the analytical basis (Li et al., 2019; McGrew et al., 2020).

Comparative Table of Mobile Platform Mobility Types

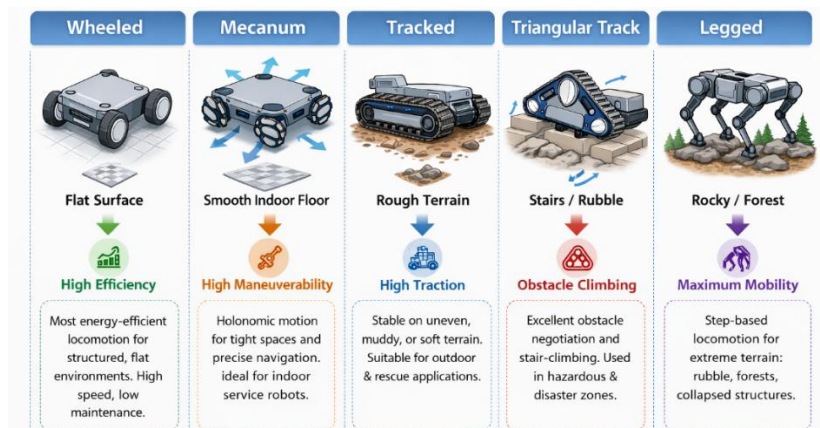


Figure 1 . Decision-flow for selecting energy supply architectures in collaborative service robots

The selection of an appropriate mobility platform is a critical design decision in collaborative mobile robotic systems. The methodology for mobility selection involves evaluating operational requirements, environmental constraints, mechanical complexity, and energy efficiency. The analysis presented in Figure 1 demonstrates that no single mobility type is universally optimal; instead, each provides distinct trade-offs.

Balance in the Choice of Power Supply for the Collaborative Robot

In collaborative robotics, a balance is sought in the power supply between high energy density, low weight, safety and the possibility of quick recharging or replacement (Chinta et al., 2025). The following table, Table 1 provides the characteristics of the types of power supply for the collaborative robot, so that a comparison can be made between each of them.

Criteria for Selecting the Type of Power Supply

Of course, there is a system of criteria for selecting the power supply for a collaborative robot intended for work in a medical facility. These requirements are determined by the specifics of the robot's activity and are relatively strict enough to obtain the expected effect of its activity (Delgado et al., 2025). For example, several such criteria can be listed as follows:

Table 1. Comparison of power supply technologies for collaborative service robots

Power supply type	Characteristics	Advantages	Disadvantages	Typical applications
1. Battery (electrochemical)	Lithium-ion, lithium-polymer, lithium-iron phosphate, nickel-metal hydride cells.	High energy density, compactness, suitable for mobility.	Limited life (cycles), risk of overheating, need for BMS.	Most mobile CSR - hospital assistants, logistics and disinfection robots.
2. Hybrid power supply. (battery + supercapacitors)	Combination of fast-discharge and long-life sources.	Extended battery life, ability to absorb peak loads.	More complex control electronics.	Robots with high starting currents (manipulators, AGV).
3. Fuel cell power supply (hydrogen or methanol).	Electrochemical conversion of fuel into electricity using PEMFC or DMFC cells.	High energy density, low noise, zero emissions (for H ₂).	System complexity, need for BOP (Balance of Plant), safety of H ₂ storage.	Robots for long-term missions — medical, rescue, military CSR.
4. Mains (stationary) power supply.	Constant power supply from the mains via adapter or transformer.	Unlimited operating time, stable voltage.	Limited mobility, need for cable management.	Stationary collaborative manipulators in laboratory and industrial environments.
5. Inductive (contactless) charging.	Energy transfer via electromagnetic induction.	Convenient, automated, no wear of connectors.	Energy losses, limited range.	Robots with periodic charging — hospital and service systems.
6. Solar power or energy recycling.	Photovoltaic panels or energy from vibrations, heat and motion.	Environmentally friendly, additional source for long missions.	Low power, strong dependence on conditions.	Robots for outdoor areas, monitoring or agriculture.

Duration of autonomous operation - requires high energy density (Li-ion, H₂ cell).

- Safety when interacting with people - low voltage
- (≤ 48 V DC), overheating protection, EMC compatibility.
- Maintenance and replacement - modularity of the battery pack, standardized connectors.
- Energy efficiency - minimal losses in converters (DC/DC, DC/AC).
- Mass and distribution of the center of gravity - important for mobile platforms.
- Environmental friendliness and sustainability - recyclable materials, low emissions.

The use of this system of criteria is quite relative and has its importance in determining the power supply system of the collaborative service robot, taking into account the restrictions imposed by the intended use, certain design limitations, and last but not least, its cost and of course the cost of the robot itself. The flowchart links mission requirements, autonomy duration, power dynamics, and mobility constraints to suitable energy solutions, highlighting hybrid fuel cell–battery architectures as a balanced choice for long-duration autonomous operation of mobile collaborative robots.

Example of Power Supply Configuration

Naturally, the selection of the type of power supply for a collaborative robot intended for use in healthcare depends on its purpose. If the robot is intended for intra-hospital transport, one type of power supply is assumed. But if this robot is intended to transport victims of car accidents or to transport them from the battlefield and the robot is capable of high cross-country ability, then obviously its power supply has certain specific requirements. In this case, a power supply is assumed that has a high energy density at a minimum volume and weight, which is sufficiently compact from a structural point of view.

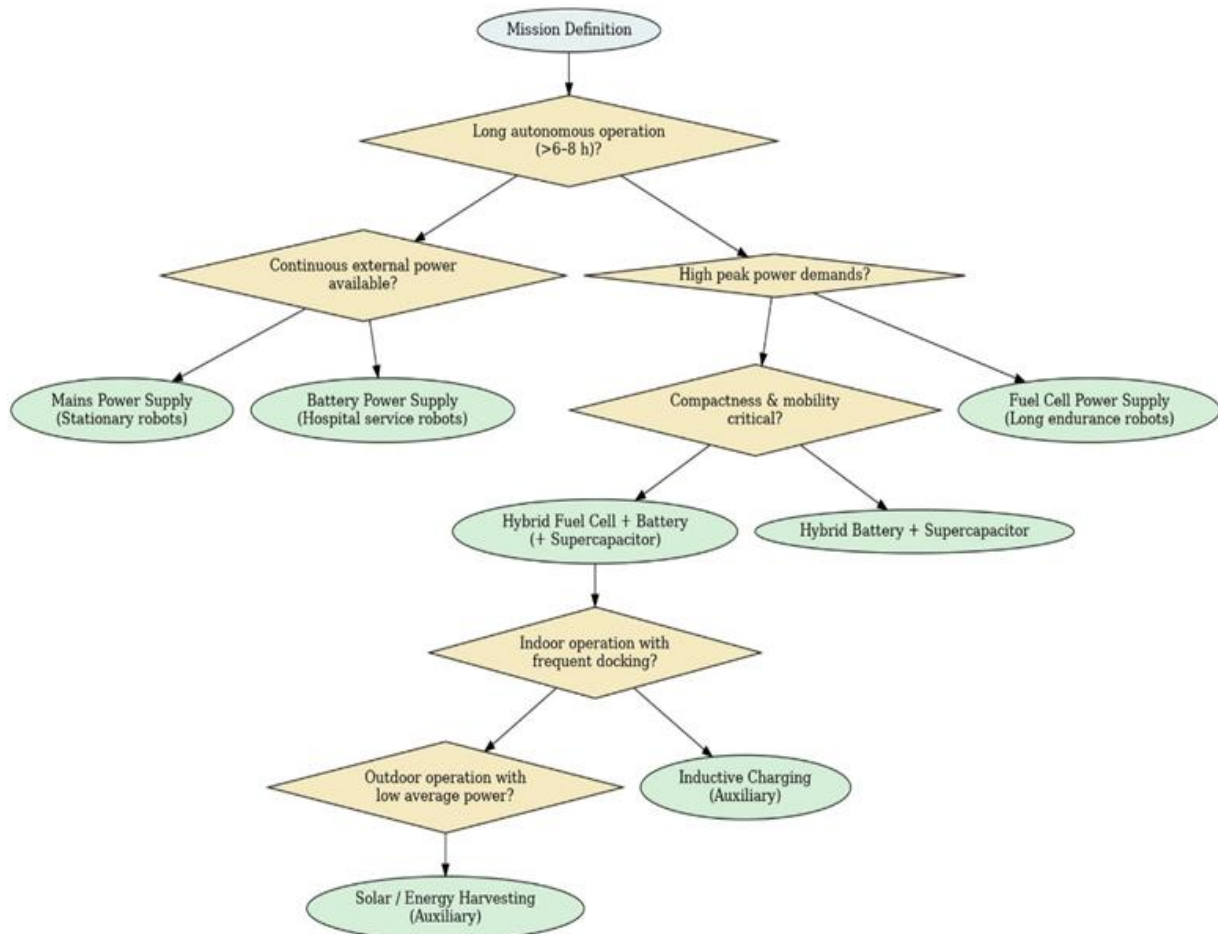


Figure 2. Decision-flow diagram for selecting an appropriate power supply architecture for collaborative service robots

As example of power supply configurations for collaborative robots used in healthcare, the following can be cited, shown in Table 1. It is interesting to analyze the data from Table 2, where the capabilities of a fuel cell combined with a Li-ion buffer so that it represents a hybrid system are immediately noticeable. The possible capacity of activity, which represents more than 12 hours of continuous operation, is remarkable. Of course, this system also has some disadvantages, such as the need to use a hydrogen tank, which is involved in the process of generating electricity. Usually, this is a metal bottle that contains hydrogen and is convenient for quick replacement with a new bottle after the first one is empty.

Table 2. Representative power supply configurations for collaborative service robots

Configuration	Voltage	Capacity	Application
Li-ion 24 V / 20 Ah + BMS	480 Wh	4–6 h autonomy	Small Mobile CSR
LiFePO ₄ 48 V / 40 Ah	1920 Wh	8–10 h operation	Medium Mobile Platforms
H ₂ Fuel Cell 500 W + Li-ion buffer	500 Wh + H ₂ tank	> 12 h continuous operation	Hybrid System
AC/DC 230 V → 24 V PSU 500 W	Continuous	Laboratory Environment	Stationary Collaborative Robot

Unfortunately, however, these bottles are significant in size and weight, which makes it difficult to constructively integrate them into the robot. With its huge capacity and ability to work continuously, this power supply system is a suitable solution for integration into a collaborative robot with high cross-country ability, which can operate in rough terrain and carry out transport operations of injured people in the open (Zhou et al., 2024). The remaining systems have their application in collaborative service robots in various cases of use where a high energy flow density is not required and it is relatively easy to recharge them for a new cycle of work (Dunn et al., 2011; Gopi et al., 2024).

Modern Trends

At the modern stage, characterized by the rapid development of Robotics, certain development trends are noticeable (Siegwart et al., 2000). This also applies to robot power supply systems and, in particular, to those systems built into collaborative service robots. With the introduction and development of control systems with elements of artificial intelligence, the management of these systems is becoming increasingly flexible and intelligent. In general, the following development trends in power supply systems can be noted:

- Intelligent energy management systems (Energy Management Systems - EMS) - dynamic distribution of energy between drive, sensors and communication.
- Modular energy architectures - the possibility of adding a secondary source (e.g. H₂ + battery).
- Fast charging stations and automated docking systems - to increase the continuity of work.
- Implementation of safe lithium iron phosphate cells (LiFePO₄) in medical collaborative service robots (CSR) due to lower fire hazard and safety in operating modes.
- Application of micro fuel cells and hybrid power units with supercapacitors (Fuel Cell + SC) for robots with a long duty cycle.

A large part of these development trends have already been implanted in real systems powering collaborative service robots. And these are not just laboratory samples, but real systems that perform the most complex service activities by relieving the heavy or monotonous work of people, for example, in healthcare.

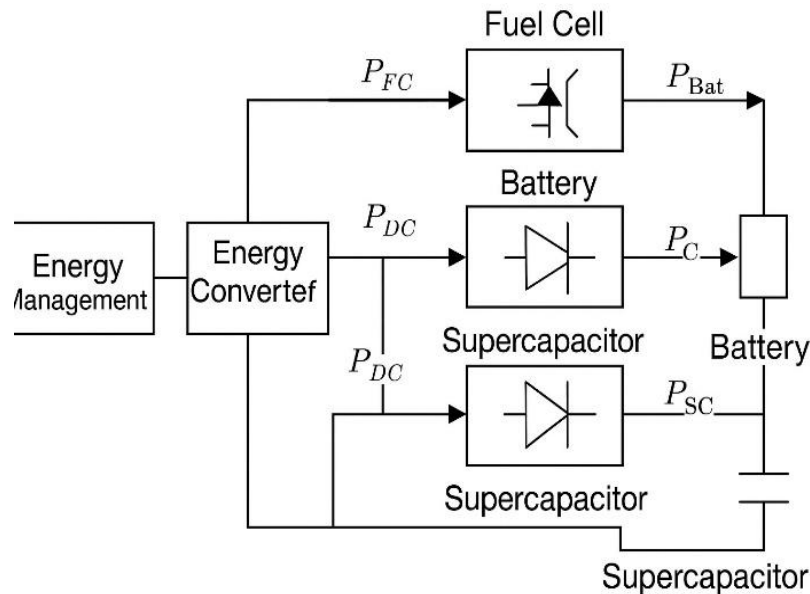


Figure 3. Schematic diagram of a combined power supply with a hybrid block.

The modern development of these systems implies increasingly complex and user-friendly new implementations that will lead to significant help to human society. An exemplary schematic diagram of a combined power supply with a hybrid energy block with supercapacitors and a battery (H2 Fuel Cell + Batt+ SC) for robots with a long duty cycle is shown on Figure 3. Such a configuration involves the use of the advantages of a micro-hydrogen fuel cell with the ability to store part of the energy in a battery. In a situation where significant power is required for a short time, the supercapacitors block is used, through which significant energy can be introduced for a very short time and thus increase the torque of the motors to a value required to overcome the obstacle that has arisen. Such a power supply system is suitable for robots with off-road capabilities in order to perform a task of transporting a seriously injured patient from a random area



Figure 4. Modern collaborative robot

Figure 4 shows a modern collaborative robot with hybrid power supply, a micro hydrogen fuel cell as a hybrid power unit with super capacitors (H2 Fuel Cell + SC) for robots with a long duty cycle. It is a wheeled platform equipped with a rich sensor system, including two types of laser interferometers (LIDAR), with the help of which it orients itself in space and is able to move to any point.

The Fuel Cell

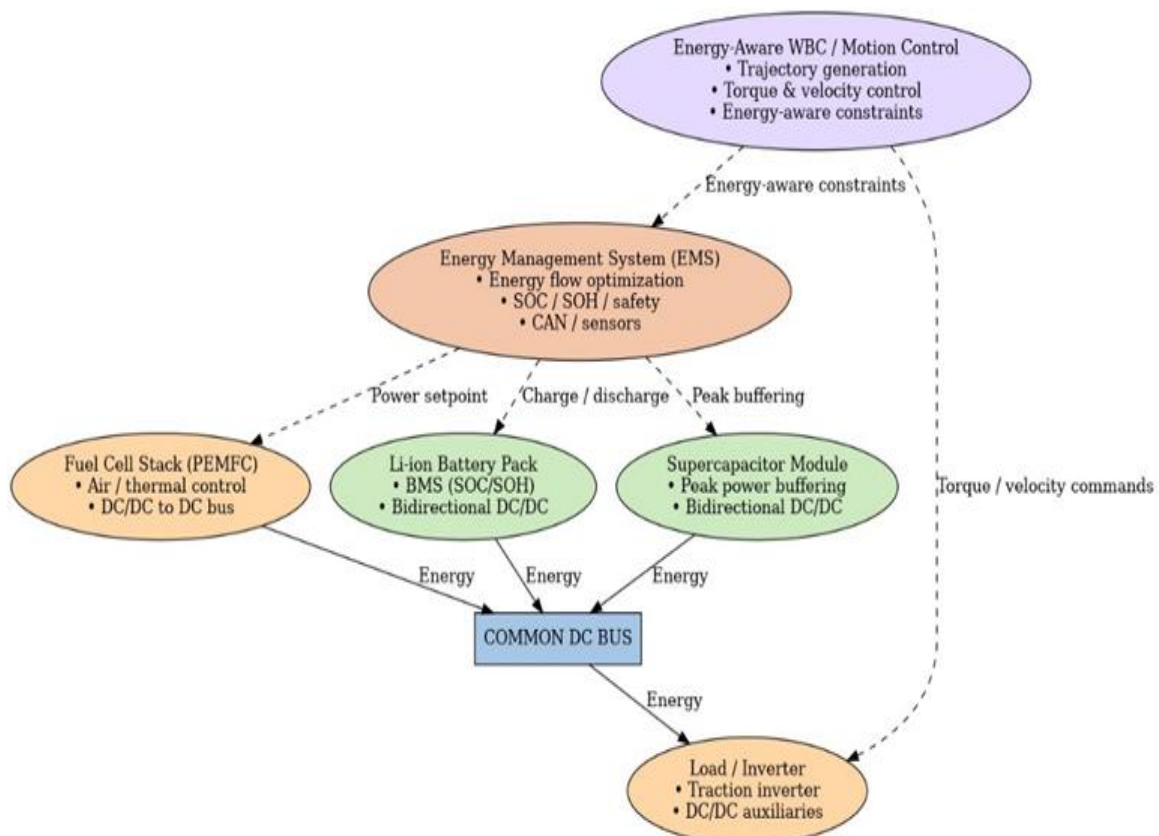


Figure 5. Diagram of the hydrogen fuel supply system of the mobile service collaborative robot.

The idea behind the fuel cell is that, in the presence of a catalyst, the water molecule initially breaks down on the surface of the electrode into two hydrogen atoms and one oxygen atom. By giving up an electron, the hydrogen atoms are oxidized to hydrogen cations. To reach the cathode, the electrons and protons take different paths. The protons pass through a membrane, while the electrons are captured by the cell's external circuit and represent ready-to-use energy. On the cathode side, in the presence of a catalyst, the protons, together with some of the electrons and oxygen, form the waste product (water vapour or pure water) from the operation of the fuel cell.

At the modern stage, characterized by the rapid development of Robotics, certain development trends are noticeable (Zhang, 2026). This also applies to robot power supply systems (Figure 5) and, in particular, to those systems built into collaborative service robots. With the introduction and development of control systems with elements of artificial intelligence, the management of these systems is becoming increasingly flexible and intelligent.

In general, the following development trends in power supply systems can be noted: Intelligent energy management systems - dynamic distribution of energy between drive, sensors and communication and application of micro fuel cells and hybrid power units with super capacitors (Fuel Cell + SC) for robots with a long duty cycle (Radmanesh, 2024).

Mathematical Model of the PEM Fuel Cell

The traction power supply of the Collaborative Robot is based on a low-temperature proton-exchange membrane (PEM) fuel cell stack. The stack voltage is modelled starting from the single-cell voltage, which is expressed as the difference between the reversible Nernst potential and the main loss components:).

$$V_{cell}(i) = E_{Nernst} - V_{act}(i) - V_{ohm}(i) - V_{conct}(i) \quad (1)$$

where i is the cell current density, E_{Nernst} is the open-circuit potential, V_{act} denotes activation losses, V_{ohm} accounts for ohmic losses in the membrane and current collectors and V_{conct} represents concentration (mass-transport) losses.

Final Stage

For the global reaction $H_2 + \frac{1}{2} O_2 \rightarrow H_2O$, the Nernst potential is

$$E_{Nernst} = E_0 + \frac{RT}{2F} \ln \left[\frac{p_{H_2} \sqrt{p_{O_2}}}{p^0} \right] \quad (2)$$

where $E_0 \approx 1.229V$ is the standard potential at $T_0 = 298K$ and $p^0 = 1atm$, R is the universal gas constant, F is Faraday's constant, and p_{H_2} and p_{O_2} are the partial pressures of hydrogen and oxygen at the anode and cathode, respectively. In the operating range considered here, the temperature dependence can be approximated by a linear correction of E_0

Activation, Ohmic and Concentration Losses

Activation overvoltage is described by a Tafel-type relation

$$V_{act}(i) = A \ln(i) + B \quad (3)$$

Where: A and B are empirical parameters identified from the low-current region of the polarization curve.

Ohmic losses are modeled as a linear function of current density:

$$V_{ohm}(i) = iR_{ohm} \quad (4)$$

With R_{ohm} representing the equivalent membrane and contact resistance, which depends on membrane hydration and temperature.

At high current densities, mass-transport limitations are captured by

$$V_{conc}(i) = -C \ln \left(1 - \frac{i}{i_{lim}} \right) \quad (5)$$

where i_{lim} is the limiting current density and C is an empirical concentration-loss coefficient. The parameters A , B , C , $Rohmandi_{lim}$ are obtained by fitting the model to the manufacturer's polarization curve of the selected stack.

Stack Voltage and Power

The 200 W fuel cell stack consists of N_{cell} identical cells connected in series, each with active area A_{cell} . For a given stack current I , the corresponding cell current density is:

$$i = \frac{I}{A_{cell}} \quad (6)$$

and the stack voltage is:

$$V_{FC}(I) = N_{cell} V_{cell} \left(\frac{I}{A_{cell}} \right) \quad (7)$$

The instantaneous electrical power delivered to the DC bus is then

$$P_{FC}(t) = V_{FC}(I(t)) I(t). \quad (8)$$

For the robot powertrain considered in this work, the stack is dimensioned for a nominal power of 200 W at approximately 48 V, leading to a nominal current of $I_{nom} \approx 4.2$ A. The model parameters are tuned such that $V_{FC} I_{(nom)} \approx 48$ V and the simulated polarization curve closely matches the datasheet.

Dynamic Extension and Simulation Implementation

To capture the transient behavior during rapid load changes, a first-order gas-dynamics model is added for the anode and cathode chambers. The partial pressures p_{H_2} and p_{O_2} are obtained from molar balance equations.

$$\frac{dn_k}{dt} = \dot{n}_{k,in} - \dot{n}_{k,react}, \quad \dot{n}_{k,react} \propto I(t) \quad (9)$$

Combined with the ideal gas law. In addition, a double-layer capacitance C_{dl} and charge-transfer resistance R_{ct} form a first-order dynamic model for the activation overvoltage. In the simulation environment, these equations are implemented as a dedicated PEMFC block providing the nonlinear voltage–current characteristic $V_{FC}(I)$ to the hybrid power-supply model of the robot.

Fuel Cell Model Validation and Empirical Analysis

Identified Parameters of the PEM Fuel Cell Model

A summary of the semi-empirical parameters obtained from fitting the fuel-cell model to the reference polarization curve provided by the manufacturer is presented in Table 4. The identified values of the Tafel slope $A=0.045$ V, Tafel intercept $B=0.12$ V and concentration-loss coefficient $C=0.015$ V exhibit typical magnitudes for low-temperature PEM cells operating near ambient conditions. The ohmic resistance $R_{ohm}=0.08 \Omega$ reflects both membrane resistance and contact losses and is consistent with the expected behavior of compact portable stacks. The estimated limiting current density $i_{lim} = 1.8 \frac{A}{cm^2}$ indicates that the stack can maintain stable operation up to 5 A without entering deep mass-transport limitation. With 68 cells and an active area of 50 cm^2 per cell, the stack achieves a nominal voltage of 48 V at approximately 4.2 A, yielding a rated power of 200 W. The inset box presents the main electrochemical and stack parameters used for system modeling. The inset box presents the main electrochemical and stack parameters used for system modeling.

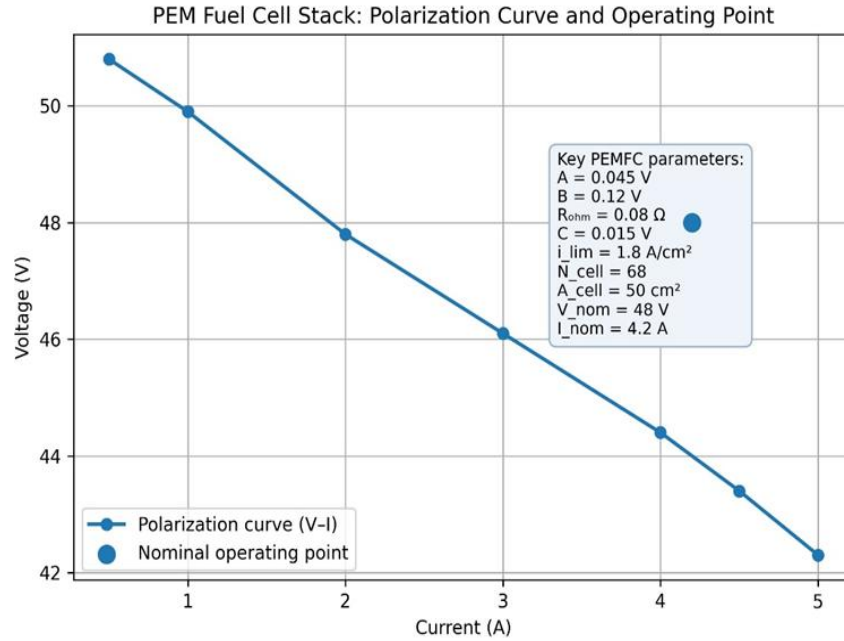


Figure 6. Polarization characteristics and nominal operating point of a PEM fuel cell stack integrated into a hybrid energy system for autonomous mobile collaborative robots.

Model Validation Against Measured Polarization Data

Table 3 presents a direct comparison between measured and modelled stack voltages across a current range of 0.5–5 A. The results demonstrate excellent agreement:

- Absolute error remains below **0.4 V** across the entire operating range.
- Relative error remains below **1%**, even near the high-current region where non-linear effects are more pronounced.

Table 3. Measured vs. modeled polarization data of the 200 W PEMFC stack

Current (A)	Measured Voltage (V)	Modelled Voltage (V)	Absolute Error (V)	Relative Error (%)
0.5	50.8	50.6	0.2	0.39
1.0	49.9	49.7	0.2	0.40
2.0	47.8	47.6	0.2	0.42
3.0	46.1	45.9	0.2	0.43
4.0	44.4	44.1	0.3	0.68
4.5	43.4	43.1	0.3	0.69
5.0	42.3	41.9	0.4	0.95

The smallest errors occur in the mid-current region (2–3 A), where activation and ohmic contributions dominate and are well captured by the semi-empirical formulation. Slightly higher deviations at 4.5–5 A are expected due to concentration effects that are more sensitive to manufacturing tolerances, humidity, and gas supply conditions. Overall, the high fidelity of the model confirms that it is suitable for energy simulation, hybrid-system control design, and performance prediction under variable load conditions.

Electrical Power Characteristics

The electrical output power computed from the measured voltage data is shown on Table 6 As expected for PEMFC technology:

- Power increases almost linearly in the low-current region due to near-constant voltage.

- A distinct **Maximum Power Point (MPP)** appears around **4.5–4.7 A**, where the product $V \cdot I$ reaches approximately **200–210 W**.
- Beyond this point, voltage drops faster than the increase in current, causing power to decline, which is typical of fuel-cell polarization behavior.

This information is particularly important for robot applications because:

- The optimal operating region lies around 80–95% of nominal load.
- Operation far above the MPP leads to higher thermal and membrane stress.
- Operation far below the MPP reduces fuel efficiency.

Table 4. Electrical power of the fuel cell stack as a function of current

Current (A)	Voltage (V)	Electrical Power (W)
0.5	50.8	25.4
1.0	49.9	49.9
2.0	47.8	95.6
3.0	46.1	138.3
4.0	44.4	177.6
4.5	43.4	195.3
5.0	42.3	211.5

Thus, the robot's hybrid powertrain (fuel cell + battery + supercapacitor) should be tuned to maintain average operating current within this efficient band.

Derived Operational Metrics

Table 5 highlights key system-level performance indicators:

- The voltage drop from open-circuit (50.8 V) to nominal load (44.4 V) is consistent with typical PEMFC internal resistance and activation losses.
- The dynamic load range (1–5 A) aligns well with the energy profile of mobile robots during acceleration, cruising, and slope climbing.
- The typical stack electrical efficiency (40–55%) matches manufacturer specifications for compact PEM systems.
- The hydrogen consumption estimate (~ 0.02 g/s at 4.2 A) provides useful context for autonomy calculations—approximately:
 - 1.2 g/min, or
 - ~ 72 g/hour at nominal operating point.

Table 5. Derived performance metrics of the 200 W PEMFC stack

Metric	Value
Maximum power point (MPP)	~ 4.7 A @ ~ 43 V
Maximum power	~ 202 – 210 W
Voltage drop from no-load to nominal	50.8 V $\rightarrow$ 44.4 V
Dynamic load range used in robot	1–5 A
Typical system efficiency range	40–55 % (stack-only)
Estimated hydrogen consumption @ 4.2 A	~ 0.02 g/s (approx.)

For mobile collaborative robots, these values imply practical run-times of several hours depending on tank size and duty cycle.

Simulation Results

This section presents the outcomes of the simulation experiment used to evaluate the performance of the hybrid hydrogen fuel cell–battery power system during a representative 30-minute rescue mission. Three key indicators were analyzed: the robot’s electrical power demand and power sharing (Figure 7), the evolution of the battery state of charge (Figure 8), and cumulative hydrogen consumption (Figure 9).

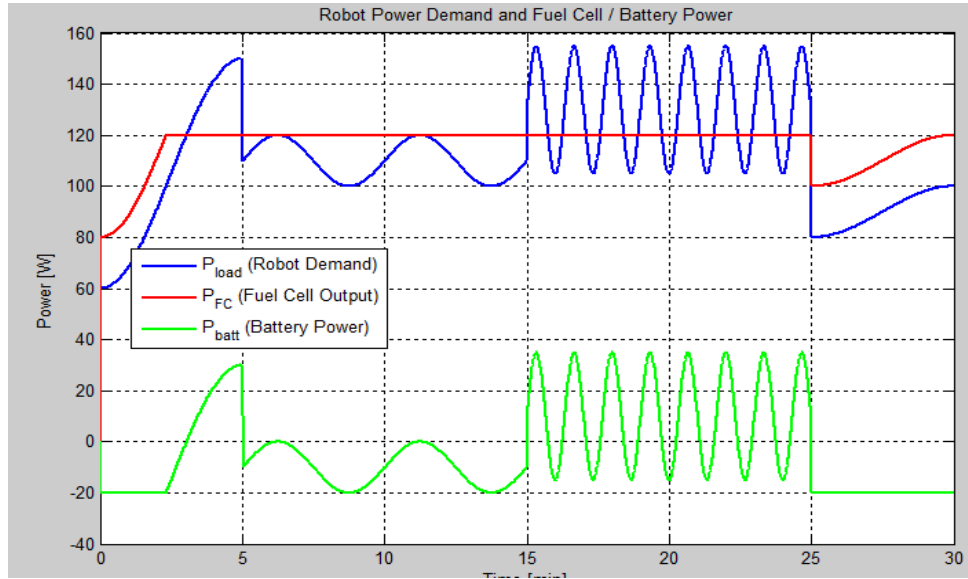


Figure 7. Robot power demand

Power Demand and Power Sharing

Figure 7 shows the interaction between the robot’s total electrical power demand (P_{load}), the fuel cell output power (PFC), and the battery power contribution (P_{batt}). The curves capture realistic operating behaviour across four mission phases.

A. Acceleration and initial activity (0–5 min)

P_{load} rises smoothly from ~60 W to ~150 W as the robot accelerates from rest.

- PFC remains near its preferred operating point (~120 W).
- The remaining power (~20–40 W) is supplied by P_{batt} (battery discharge).

This demonstrates the fuel cell’s role as a stable energy source and the battery’s function as a high-response auxiliary power provider.

B. Steady straight motion (5–15 min)

During straight-line travel, P_{load} stabilizes around 110 ± 10 W.

- PFC closely matches the load.
- P_{batt} oscillates near zero, occasionally negative (charging) when PFC slightly exceeds instantaneous demand.

This reflects efficient hybrid operation with minimal battery cycling.

C. Circular/turning manoeuvres (15–25 min)

Turning and directional adjustments generate higher dynamic loads, oscillating around 130 ± 25 W.

- PFC remains relatively constant (~120 W).
- P_{batt} alternates between positive and negative values, absorbing fast changes and stabilizing the DC bus.

This shows the battery's essential role in compensating for rapid load variations that the fuel cell cannot follow instantaneously.

D. Return and low-speed manoeuvring (25–30 min)

The load reduces to 80–100 W as the robot slows down and stabilizes.

- PFC remains slightly above P_{load} , resulting in mild battery charging.

Overall, Fig. 5 confirms that the hybrid fuel cell–battery system supports both the baseline continuous demand and transient events typical of a rescue robot.

Battery State of Charge

Figure 8 shows the evolution of the battery state of charge (SOC) during the mission.

- SOC decreases from 80% at the start to approximately 65–70% at the end of 30 minutes.
- This gradual decline indicates:
 - the battery is not overused or overstressed,
 - peak demands are properly buffered,
 - the hybrid system is correctly sized.

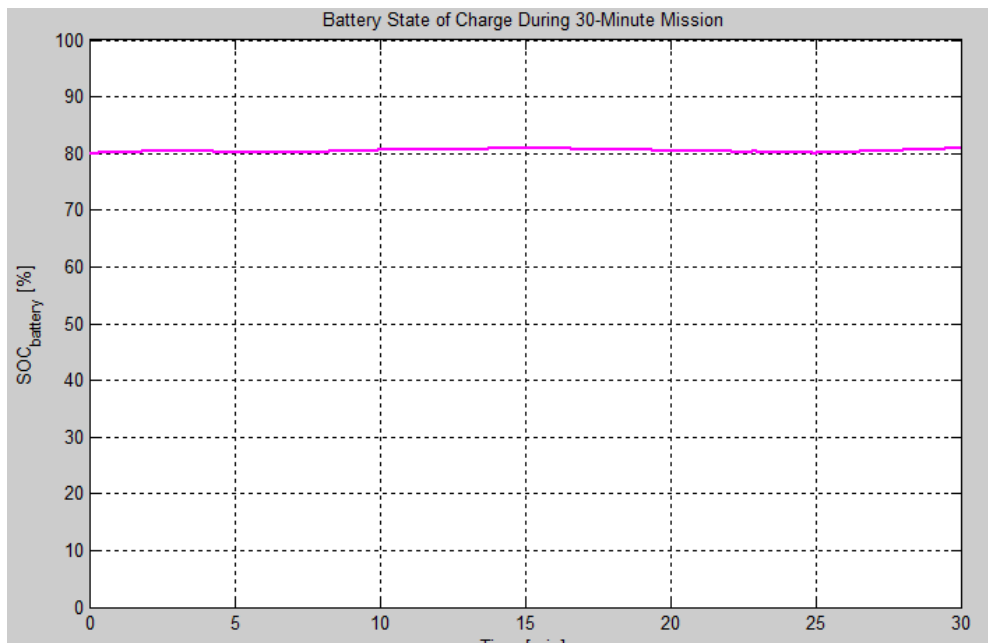


Figure 8. Battery SOC.

Moderate SOC consumption suggests the battery can support significantly longer missions if required.

Hydrogen Consumption

Figure 9 presents the cumulative hydrogen consumption over time, based on the fuel cell's delivered electrical energy and the assumed specific energy of: $1 \text{ kg H}_2 = 23 \text{ kWh}$.

- Over the full 30-minute mission, hydrogen usage remains below 6 g, which corresponds to the capacity of the modelled hydrogen cartridge.
- The curve increases smoothly and almost linearly, reflecting the near-constant fuel cell operating power (~120 W).

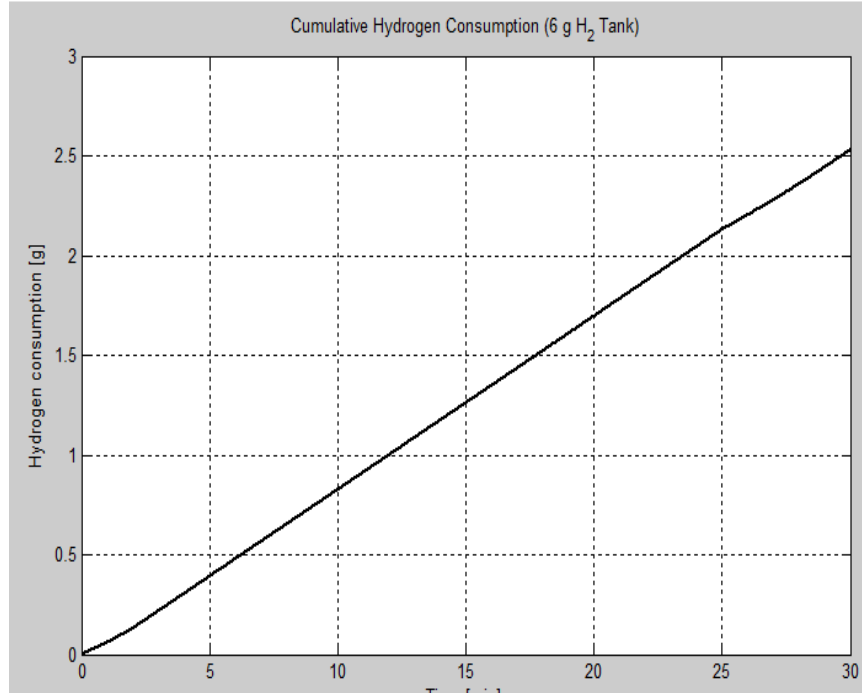


Figure 9. Hydrogen consumption during mission.

This confirms the feasibility of using compact hydrogen cartridges to power service robots in field of medical applications.

Summary of Findings

- The hybrid power system effectively handles dynamic real-world loads (acceleration, steady motion, turning), as shown in Fig. 7.
- Battery SOC remains within a safe, moderate operating band (Fig. 8).
- Hydrogen consumption remains within small-cartridge limits (Fig. 9).

The simulation demonstrates that a hybrid PEM fuel cell–battery system can effectively support the variable load profile of a collaborative rescue robot during a 30-minute mission. The fuel cell provides a stable baseline power level, while the battery supplies fast transient loads during acceleration and turning manoeuvres. The hydrogen consumption remains below 6 g for the entire mission, validating the feasibility of lightweight hydrogen energy modules for field medical robotics. The SOC evolution confirms that the battery experiences moderate cycling, suggesting extended lifetime and high reliability. These results collectively indicate that hydrogen fuel cells, even at small scales, can significantly extend mission autonomy while maintaining stable power delivery under dynamically changing operational conditions.

Link Between Robot Movement, PID Control and Power Profiles

The robot's motion during the simulated mission is governed by a standard PID velocity controller that regulates wheel or track motor speeds in response to the desired velocity profile. The PID loop directly influences both the instantaneous electrical load on the drivetrain and the shape of the P_{load} curve in Fig. 7.

PID Control and Motion Dynamics

The robot uses a closed-loop velocity controller of the form:

$$u(t) = K_P e(t) + K_I \int e(t) dt + K_D \frac{de(t)}{dt} \quad (1)$$

Where:

- $e(t)$ is the velocity error,
- K_P , K_I , K_D , are the controller gains,
- $u(t)$ is the motor command (torque/current demand).

During the mission:

- Changes in $v_{rfe}(t)$ (acceleration, turning, deceleration) cause transient velocity errors.
- The PID controller responds with increased motor torque commands.
- Motor torque demand translates directly into increased electrical power demand from the energy subsystem.

This control loop creates the characteristic peaks and oscillations seen in P_{load} in Fig. 7.

How PID Dynamics Shape Fig. 7 (P_{load} , P_{FC} , P_{batt})

A. Acceleration Phase (0–5 min)

At the beginning of motion, velocity error is high.

- The PID proportional term generates large torque requests.
- The derivative term stabilizes the response but also amplifies sharp changes in speed command.

A smooth but pronounced rise in P_{load} (Fig. 7) representing the increased electrical power needed to accelerate the robot.

Battery participation ($P_{batt} > 0$) appears because the fuel cell alone cannot instantaneously supply rapid increases in motor demand.

B. Steady Straight Motion (5–15 min)

Velocity error approaches zero and PID output stabilizes.

- Motor torque requirement becomes nearly constant.
- The controller settles into low-effort regulation.

P_{load} stabilizes around 110 ± 10 W, with minor fluctuations due to noise, micro-corrections, and terrain irregularities.

The fuel cell outputs almost all required power; the battery rests or charges slightly.

C. Circular / Turning Motion (15–25 min)

During turning, left/right wheels or tracks rotate at different speeds.

This causes alternating velocity errors on each side:

- PID controllers on each wheel produce oscillatory torque corrections.
- The robot experiences repeated micro-acceleration and micro-deceleration.

Oscillatory P_{load} around 130 ± 25 W.

These sinusoidal power fluctuations correspond to cyclic correction of velocity error during steering.

Because the fuel cell remains at a stable setpoint (~ 120 W), the battery absorbs and supplies the difference.

This results in the green P_{batt} curve fluctuating above and below zero.

D. Deceleration / Return Phase (25–30 min)

The desired velocity profile reduces smoothly.

- PID output decreases,
- Motors draw less torque,
- P_{load} decreases to 80–100 W, reflecting reduced kinetic demand.

Some negative P_{batt} values appear as the fuel cell now slightly overpowers the load and recharges the battery.

PID Control Role in Hybrid Power Management

PID-induced torque demands translate into high-frequency power fluctuations at the motor drivers.

Fuel cells cannot respond to high-frequency transients because of:

- slow electrochemical dynamics,
- limited ramp rate,
- efficiency losses under rapid load swings.

Therefore:

- The fuel cell handles *low-frequency, average* power (red curve in Fig. 7).
- The battery handles *high-frequency, transient* power (green curve).

This division of roles is exactly what hybrid FC–battery systems are designed for, and the simulation results visualize this elegantly.

Summary

The dynamic shape of the power demand curve (Fig. 7) is a direct consequence of the PID velocity control loop responsible for regulating wheel/track speeds. Transient velocity errors during acceleration, turning, and manoeuvring generate short-duration torque peaks, which appear in Fig. 1 as oscillations in the P_{load} signal. Because the fuel cell operates optimally at a near-constant power, these PID-induced transients are supplied by the battery (P_{batt}), while the fuel cell maintains the baseline demand (PFC). This behavior confirms the correct functional integration of the hybrid energy system and the motion control subsystem.

Conclusion

The type of power supply for collaborative service robots is determined by the mission, the operating environment and safety requirements. The most flexible solutions are hybrid systems (battery + supercapacitors or battery + fuel cell), which provide an optimal balance between energy density, peak capacity and operational reliability. In future developments, the trend is towards “smart” power modules that self-optimize according to the load and allow collaborative work in a dynamic environment without interruption. Based on the above, the following conclusions can be drawn:

- For mobile collaborative robots: LiFePO₄ is preferred due to safety and stability.
- For high-performance platforms or long autonomous missions: the hydrogen fuel cell is an excellent choice.
- For high peak loads and recuperation: supercapacitors are often combined with batteries (hybrid power supply).

This work introduced a comprehensive methodology for the energy-aware design and evaluation of a four-wheeled collaborative robot powered by a hybrid system comprising a 200 W PEM fuel cell, battery storage, and power electronics.

A nonlinear semi-empirical mathematical model of the PEM fuel cell was developed, incorporating activation, ohmic and concentration losses, and validated against measured polarization data. The model demonstrated high fidelity, with a relative voltage error below 1% across the 0.5–5 A operating range, confirming its suitability for

energy-flow prediction and hybrid-system optimization. The identification of the stack's maximum-power region (approximately 4.5–4.7 A, 200–210 W) provides a robust reference for controller design and load-sharing strategies.

The methodology is directly applicable to next-generation field-deployable and autonomous service robots operating in energy-constrained environments, where efficiency, reliability, and sustained power delivery are essential. Future research will extend this framework to include adaptive PID tuning, data-driven degradation modeling of the fuel-cell membrane, and hardware-in-the-loop validation using the complete hybrid power system

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

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* The authors declare that they have no conflicts of interest.

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Author(s) Information

Nina Valchkova

Bulgarian Academy of Sciences
Akad. Georgi Bonchev“ str. block 2, Sofia, Bulgaria
ORCID iD: <https://orcid.org/0000-0002-8942-7021>

Vasil Tsvetkov

Bulgarian Academy of Sciences
Akad. Georgi Bonchev“ str. block 2, Sofia, Bulgaria
ORCID iD: <https://orcid.org/0009-0000-9163-1614>
*Contact e-mail: vasil.tsvetkov.ir@gmail.com

Georgi Angelov

Bulgarian Academy of Sciences
Akad. Georgi Bonchev“ str. block 2, Sofia, Bulgaria
ORCID iD: <https://orcid.org/0000-0002-5229-4763>

Roman Zahariev

Bulgarian Academy of Sciences
Akad. Georgi Bonchev“ str. block 2, Sofia, Bulgaria
ORCID iD: <https://orcid.org/0000-0002-9914-3284>

Yasen Paunski

Bulgarian Academy of Sciences
Akad. Georgi Bonchev“ str. block 2, Sofia, Bulgaria
ORCID iD: <https://orcid.org/0000-0002-4516-5330>

*Corresponding author(s) email

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A Machine Learning Framework for Long-term Precipitation Prediction Using Gradient Boosting and Ensemble Techniques

Nexhmije Miftari

Mother Teresa University

Valon Ahmeti

Mother Teresa University

Majlinda Axhiu

Mother Teresa University

Abstract: Long-term precipitation prediction remains a challenging task due to the nonlinear and dynamic interactions among meteorological variables, particularly in regions with complex climatic conditions. This study proposes a Machine Learning framework based on XGBoost combined with temporal feature engineering for predicting rainfall, snowfall, and total precipitation in North Macedonia. Given the limitations of traditional numerical weather prediction models and the lack of region-specific studies focused on the Balkan climate, this research investigates whether advanced supervised learning algorithms can improve the accuracy and stability of precipitation forecasting. A comprehensive dataset covering the period from 2000 to 2025 was obtained from Visual Crossing, followed by extensive preprocessing and feature engineering. The engineered features include lag variables, rolling statistics, seasonal indicators, and interaction terms to better capture temporal dependencies and complex relationships in the data. Three predictive models were developed: a rainfall classifier, a snowfall classifier, and a general precipitation classifier. The primary algorithm employed was XGBoost, while the snowfall prediction model utilized an ensemble stacking approach combining XGBoost, Random Forest, and LightGBM to address class imbalance and enhance model robustness. Model validation was conducted using a TimeSeriesSplit strategy with temporal gaps to prevent data leakage. The results demonstrate significant performance improvements using gradient boosting-based methods. The snowfall model achieved an accuracy ranging from 90% to 97%, rainfall prediction reached 81% to 84%, and the general precipitation model achieved 80% to 81% accuracy. Feature importance analysis identified temperature, humidity, atmospheric pressure patterns, and cloud cover as the most influential predictors. These findings confirm that machine learning provides a reliable and effective approach for long-term precipitation forecasting in the region, with potential applications in agriculture, transportation, and environmental planning.

Keywords: XGBoost, Random Forest, LightGBM, Precipitation prediction, Predictive machine learning.

Introduction

Accurate forecasting of precipitation is essential for many sectors, including agriculture, transportation, and urban development. Long-range predictions continue to be problematic due to the intricate relationships among atmospheric factors, as highlighted by Doblas-Reyes et al. (2013). This difficulty is particularly noticeable in North Macedonia, where the combination of continental and Mediterranean climates generates a considerable amount of change in local weather (Schaer et al., 2016).

Traditional forecasting methods including numerical forecast models are based on physical equations and large scale simulations. While these methods are essential, they require a lot of computing power and can be sensitive

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to the initial conditions (Hoffman & Kalnay, 1983). Furthermore, statistical approaches like linear regression or ARIMA frequently have trouble with the nonlinear dynamics found in meteorological measurements. In this context, machine learning is emerging as a promising option. By utilizing past data, it can determine complicated patterns without being dependent on defined physical principles (Agarwal & Kumar, 1983). XGBoost, among the different options, has shown excellent results with structured data because of its ability to model nonlinear interactions (Chen & Guestrin, 2016).

Using long-term meteorological data from Skopje this study aims to create a solid ML framework for predicting rainfall, snowfall and total precipitation. The focus is in particular building multiple predictive models suited to different types of precipitation using feature engineering techniques to capture temporal dependencies assessing model performance with time-aware validation strategies and analyzing feature importance to gain insights.

Method

Dataset and Preprocessing

The data is a collection of daily weather readings from 2000 to 2025, a total of over 9,000 entries and more than 30 different measurements. These measurements cover temperature, how much moisture is in the air, air pressure, details about the wind, how cloudy it is, and how much rain or snow falls.

Data preprocessing was performed in several stages. First, any measurement that was missing for more than 30% of the time was dropped, because we wanted to be sure the data was trustworthy. Remaining missing values were handled using appropriate imputation strategies, taking into account the nature of each variable. Additionally, highly correlated features ($|p| > 0.95$) were removed to avoid things being over-emphasized and to help avoid problems with variables affecting each other. For the model specifically designed to predict snowfall, we only used data from December to March. This decision was based on preliminary observations indicating that including non-winter data introduced noise without improving the accuracy of the prediction.

Feature Engineering

Feature engineering was a key component of this study. Rather than relying solely on daily observations, additional features were constructed to capture temporal dynamics and interactions among variables. These included:

- lag features representing values from previous days
- rolling statistics (e.g., 3-day and 7-day averages and standard deviations)
- interaction features such as humidity $\times$ cloud cover
- temporal indicators including month, season, and day-of-year

These adjustments helped the model be more aware of how the past affects the present, and the overall build-up of conditions in the atmosphere, both of which are often crucial to understanding rainfall and snowfall.

Model Development and Evaluation

In our study we developed three predictive models, including: a rainfall classification model, a snowfall classification model and a total precipitation regression model. XGBoost was selected as the primary algorithm due to its efficiency and ability to capture nonlinear relationships. The model builds an ensemble of decision trees iteratively, minimizing prediction errors at each step (Chen & Guestrin, 2016). The snowfall model beside XGBoost, in order to align the class imbalance also included Random Forest and LightGBM techniques.

We carefully adjusted the settings of all the forecasting systems using grid search and cross-validation. What we tweaked – the number of ‘trees’ in the collection, how quickly the system learns, how far each ‘tree’ can branch, and how to avoid being overly specific to the training data – was all to get the best possible outcome that also works with new data. Figure 1 presents the most influential features for the rainfall prediction model. The results show that humidity and cloud cover are the dominant predictors, particularly through interaction features such as humidity and cloud cover and cloud cover and temperature. This indicates that rainfall is primarily driven by moisture related conditions rather than individual variables in isolation.

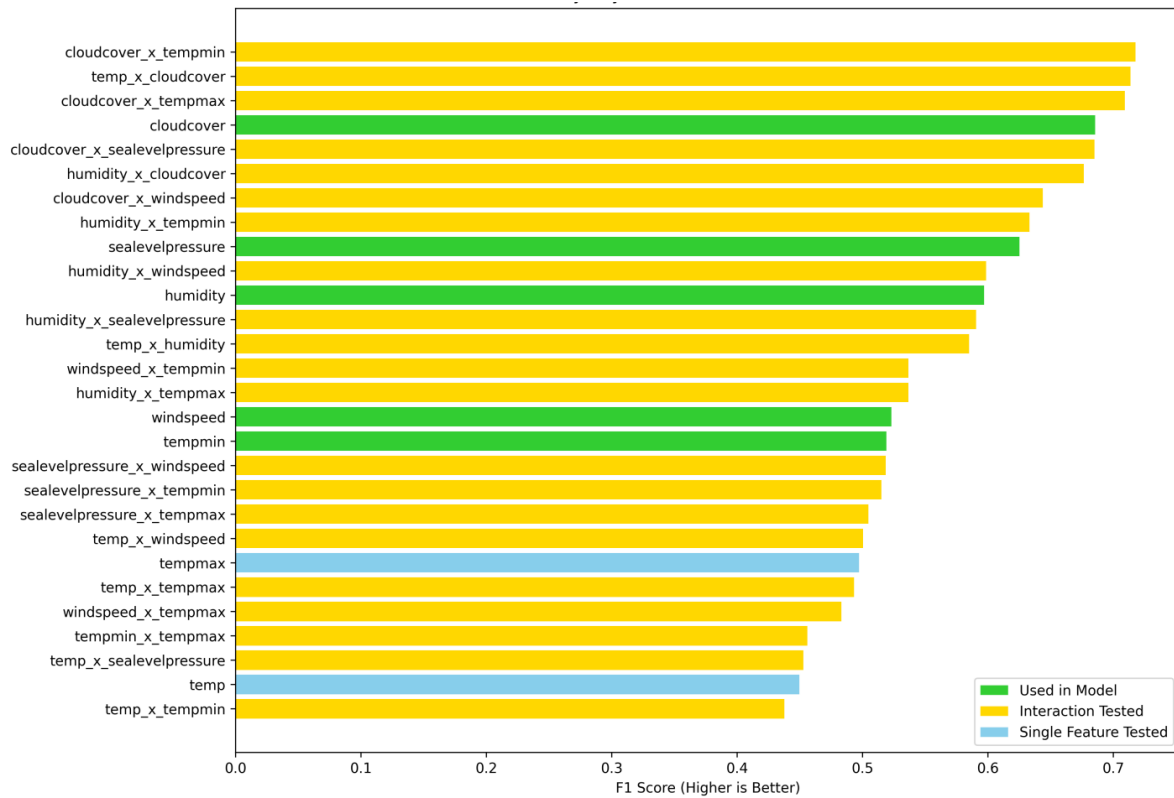


Figure 1. Feature importance and interaction effects for the rainfall prediction model (F1 score).

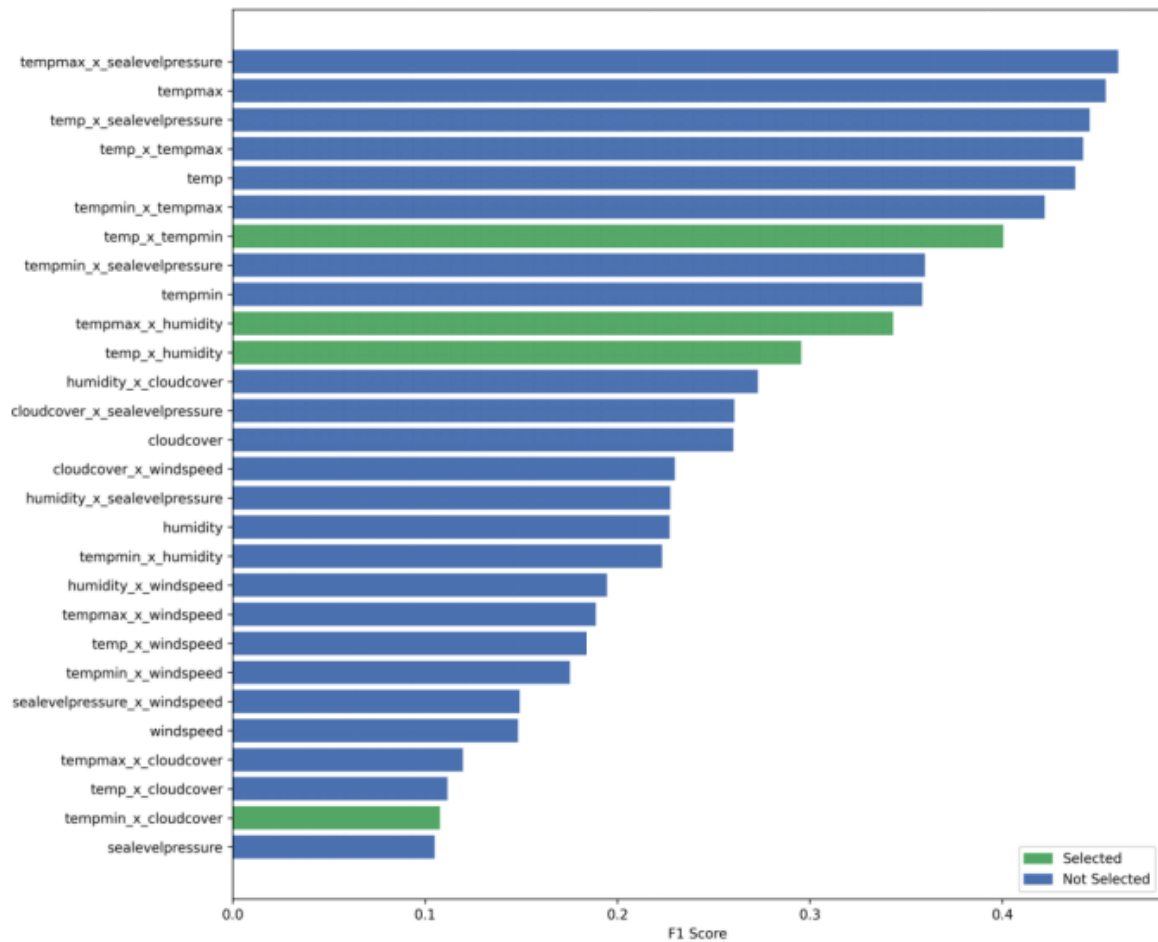


Figure 2. Feature importance and interaction effects for the snowfall prediction model (F1 score).

Compared to snowfall, temperature has a more indirect role, mainly through its interaction with other features. This suggests that rainfall formation depends on combined atmospheric dynamics rather than strict thermal thresholds. As illustrated in Figure 2, the variables that most influence predictions of snowfall are related to temperature. Maximum temperature and sea level pressure interactions are especially significant, a finding in line with what we understand about snowfall's reliance on temperature. The snowfall prediction model's important variables are arranged in a more defined, focused manner than those for rainfall. This is probably because snowfall is strongly tied to the time of year. Interactions between variables are still important but are predominantly those of temperature.

Interestingly, a number of the characteristics chosen for inclusion are not the very best predictors when looked at on their own. This happens because the way we selected features looks at how they work together, rather than how useful each is in isolation. Specifically, some features representing interactions between variables might be fairly average by themselves but greatly improve the model's accuracy when used alongside other characteristics. Furthermore, if strong predictors are very similar to each other, the process may leave out a strong predictor to select a group of characteristics that work better together.

In contrast to the individual models, the complete precipitation model, illustrated in Figure 3, accounts for a wider variety of factors influencing precipitation, and is therefore more broadly applicable, though somewhat less detailed. However, the findings do demonstrate that including interactions and how things change over time makes predictions better and provides a more accurate depiction of what happens in the atmosphere.

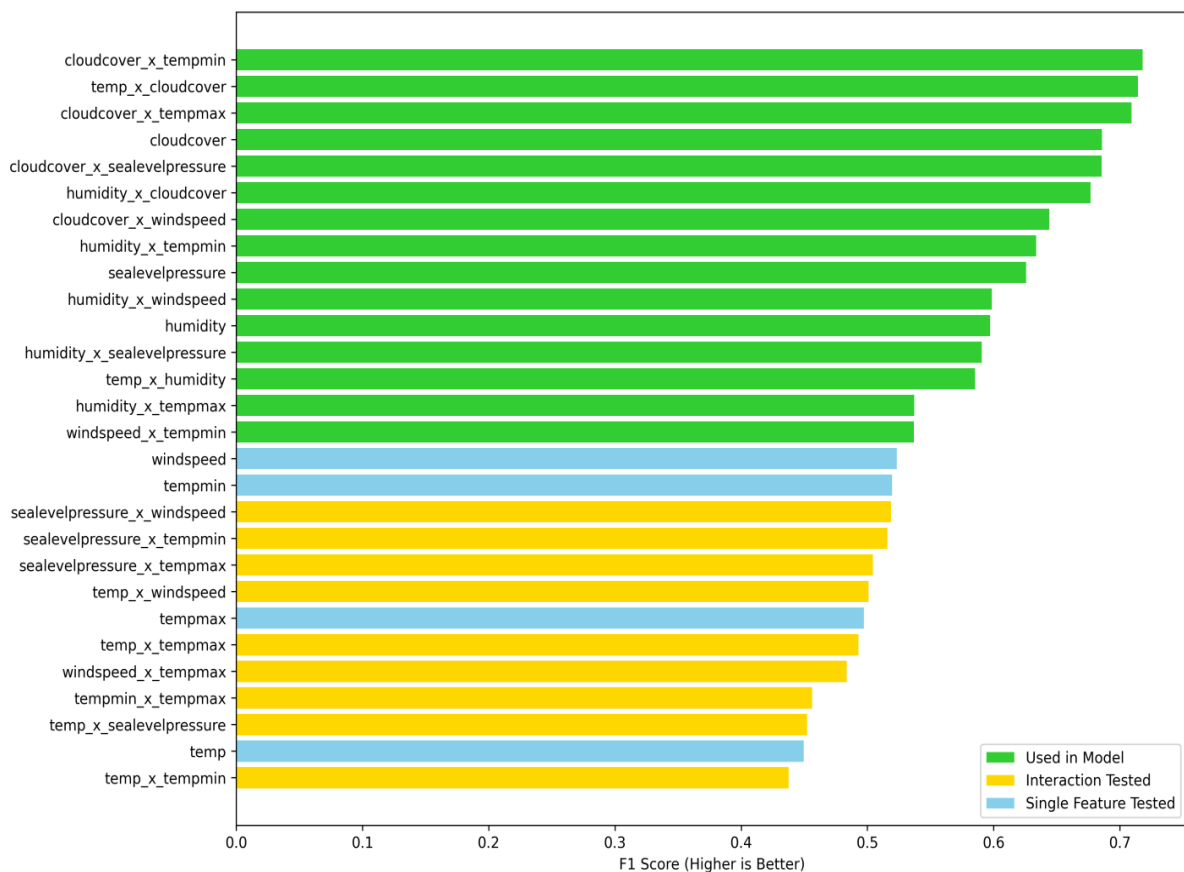


Figure 3. Feature importance and interaction effects across precipitation model (F1 score).

We assessed the models' effectiveness with a five-fold TimeSeriesSplit cross-validation. This method respects the chronological sequence of the data and prevents the unintentional use of future information to predict past outcomes, a crucial consideration in forecasting with time-series.

Results and Discussion

The outcomes demonstrate that all models functioned reliably and at a good standard.

Table 1. Performance of the models

Model	Accuracy
Snowfall	90-97%
Rainfall	81-84%
Percipitation	80-81%

The snowfall model was the most accurate. This is probably because of the more defined seasonality and obvious relationship to temperature. Similar observations have been reported in previous studies (Sanches et al., 2024; Pola & Sekhar, 2021). In the analysis of which features were most important, we identified several primary influences: temperature is the most significant factor in determining snowfall, humidity and cloud cover are tightly connected to rainfall, and previous data points (lag features) greatly improve how well the predictions are made. These findings are in line with what is already known in meteorology and indicate the model is identifying real physical connections, not coincidental associations.

These results support the use of XGBoost for modelling rainfall patterns in complicated climates. In contrast to standard statistical methods, the model is much more easily adjusted to accommodate non-linear relationships and interactions between variables. However, we must also acknowledge certain weaknesses. The effectiveness of the model relies on having good quality, comprehensive data. Furthermore, infrequent or very severe weather occurrences are hard to forecast, as they are not generally found in many historical data sets.

Conclusion

The outcomes of this research validate the efficacy and dependability of XGBoost and ensemble models for predicting rainfall and snowfall over the long term in Skopje, North Macedonia, within a machine learning framework. Accuracy and the ability to apply the predictions to new situations are both notably enhanced when compared to standard methods. In addition to being accurate in their predictions, the results reveal which meteorological variables are most important, and thereby offer a more complete understanding of how precipitation occurs. However, the analysis is still restricted by its reliance on data from only one source and by the absence of precipitation measurements from satellite or radar.

Recommendations

Considering these findings, there are multiple avenues for further investigation. Expanding the data set to include more than just Skopje would be beneficial in determining how applicable the method is to other areas that have different climates. A broader geographical investigation will enhance the solidity of the conclusions. Furthermore, including data from satellites or live observations could enhance the performance of the model, especially in predicting infrequent or severe weather that is not adequately documented in past data. Future research could also assess combined methodologies that link machine learning to physical models. Such a fusion may achieve a stronger equilibrium between predictive precision and how easily the predictions can be explained in terms of physics. And from a functional viewpoint, this system could be transformed into decision making assistance for areas such as farming or city development, both of which would greatly benefit from knowing precipitation levels ahead of time.

Scientific Ethics Declaration

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Author(s) Information

Nexhmije Miftari

Mother Teresa University
“1669” nr. 11A, Skopje, North Macedonia
ORCID iD: <https://orcid.org/0009-0004-6774-2321>

Valon Ahmeti

Mother Teresa University
“1669” nr. 11A, Skopje, North Macedonia
ORCID iD: <https://orcid.org/0009-0001-3060-1929>

Majlinda Axhiu

Mother Teresa University
“1669” nr. 11A, Skopje, North Macedonia
ORCID iD: <https://orcid.org/0000-0002-2567-1623>
*Contact e-mail: majlinda.axhiu@unt.edu.mk

*Corresponding author(s) contact email

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Common Fixed-Point Results for Geraghty-Ciric Contraction in Fuzzy Metric Space

Eriola Sila

University of Tirana

Dritan Gerbeti

University 'Luigj Gurakuqi'

Silvana Liftaj

University of Aleksander Moisiu

Abstract: The theory of fixed points has undergone significant development over the years through the generalization of contraction conditions and the modification of the axioms of metric spaces. These advancements have broadened the applicability of fixed-point results across various branches of mathematics and applied sciences. In particular, fuzzy metric spaces have provided a flexible and effective framework for dealing with uncertainty, leading to a growing interest in the study of contractive mappings within this setting. In this paper, we investigate common fixed-point results for a pair of weakly compatible mappings satisfying a Geraghty-Ćirić-type contraction condition in the context of complete fuzzy metric spaces. By using the properties of Cauchy sequences and convergence in fuzzy metric spaces, we establish sufficient conditions for the existence and uniqueness of a common fixed point for the mappings under consideration. The results obtained in this work extend and generalize several known theorems in the existing literature, especially those related to Geraghty- and Ćirić-type contractions. To demonstrate the applicability of the main theorem, an illustrative example is provided. Furthermore, a corollary is derived as a special case of the main result, highlighting its versatility and potential for further generalizations.

Keywords: Fixed point, Fuzzy metric space, Geraghty-Ciric contraction, Cauchy sequence, convergent sequence

Introduction

Fixed point theory has played a fundamental role in nonlinear analysis since Banach contraction principle was stated (Banach, 1922). Over the years, numerous generalizations of contractive conditions and metric spaces have been introduced to broaden the applicability of fixed-point results. In this direction, the development of fuzzy metric spaces brought a new perspective to fixed point theory.

The Theory of Fuzzy Sets was introduced by Zadeh (1965), marking a revolution in mathematics Kramosil and Michalek (1975) gave the definition of a fuzzy metric space by changing the metric axioms using a third variable time, which measures the distance between points (Kramosil & Michalek, 1975). Later, George and Veeramani generalized the axioms of a fuzzy metric space and studied fixed-point theorems. Nowadays, their definition is widely used because it relates to convergence and Cauchy sequences (George and Veeramani, 1994). Many authors have worked in this direction, giving their contribution to fixed point theory in fuzzy metric spaces (Moussaoui, 2025; Gerbeti et al., 2025; Ghods, 2022; Huang, et al, 2021).

Shamas et al. (2021) introduced the notion of Ćirić-type fuzzy contraction mappings and established a fixed point theorem in the setting of fuzzy metric spaces (Building on these developments, Shu-Fang Li et al. proposed new Geraghty- and Ćirić-type contractive mappings and derived a corresponding fixed-point result in the framework of a complete metric space (Li, 2022). Inspired by the aforementioned authors, in this paper, we introduce a pair of Geraghty–Ćirić-type functions in fuzzy metric spaces and establish the existence and uniqueness of a fixed point for this pair of mappings. Our result generalizes the theorem of Li et al. (2022) as we establish the existence and uniqueness of a common fixed point for a pair of weakly compatible functions.

Preliminaries

Definition 1. (Zadeh, 1965) A binary operation $*$: $[0,1] \times [0,1] \rightarrow [0,1]$ is a continuous triangular norm or t-norm if it satisfies the following conditions:

1. $a * 1$ for all $a \in [0,1]$;
2. $*$ is an associative operation.
3. $a * b \leq c * d$ whenever $a \leq c$ and $b \leq d$ and $a, b, c, d \in [0,1]$;
4. $*$ is continuous.

Definition 2. (Zadeh, 1965) The 3-triple $(X, M, *)$ called a fuzzy metric space if X is an arbitrary nonempty set, $*$ is a continuous t-norm and M is a fuzzy set on $X \times X \times (0, \infty)$ satisfying the following conditions

1. $M(x, y, t) > 0$ for every $x, y \in X, t \in (0, \infty)$;
2. $M(x, y, t) = 1$ if and only if $x = y$;
3. $M(x, y, t) = M(y, x, t)$;
4. $M(x, y, t + s) \geq M(y, x, t) + M(y, x, s)$;
5. $M(x, y, t + s): (0, \infty) \rightarrow (0, 1]$ is continuous for $x, y \in X, t, s \in (0, \infty)$.

Definition 3. (Zadeh, 1965) Let $(X, M, *)$ be a fuzzy metric space and let $\{x_n\}$ be a sequence in X . Then

1. $\{x_n\}$ is convergent, if there exist $x \in X$ such that $\lim_{n \rightarrow \infty} M(x_n, n, t) = 0$ for every $t > 0$.
2. $\{x_n\}$ is a Cauchy sequence if for every $\varepsilon \in (0, 1)$ and $t > 0$, there exist $n_0 \in \mathbb{N}$ such that for every $n, m, \geq n_0$, $M(x_n, x_m, t) > 1 - \varepsilon$;
3. $(X, M, *)$ is complete if every Cauchy sequence convergent.

Shamas et al. (2021) defined Ćirić-type fuzzy contraction mappings and proved a fixed point theorem on a fuzzy metric space.

Definition 4. (Shamas et al. 2021) Let $(X, M, *)$ be a complete fuzzy metric space. A mapping $f: X \rightarrow X$ is said to be a Ćirić contraction if there exist $\alpha \in (0, 1)$ such that

$$\frac{1}{M(fx, fy, t)} - 1 \leq \alpha \max \left\{ \frac{1}{M(x, y, t)} - 1, \frac{1}{M(x, fy, t)} - 1, \frac{1}{M(fx, y, t)} - 1, \frac{1}{M(x, fx, t)} - 1, \frac{1}{M(y, fy, t)} - 1 \right\}$$

for each $x, y \in X, t \in (0, \infty)$.

Li et al. (2022) present Geraghty and Ćirić type contractive mapping and gave a fixed point result related to them in a complete metric space.

Definition 5. (Li et al. 2022) Let (X, d) be a complete metric space. The map $f: X \rightarrow X$ is called a Geraghty-Ćirić-type contraction mapping if there exist

$$\beta \in S = \left\{ R^+ \rightarrow [0, 1), \lim_{n \rightarrow \infty} \beta(s_n) = 1 \Rightarrow \lim_{n \rightarrow \infty} s_n = 0 \right\}$$

such that for each $x, y \in X$ and

$$M(x, y) = \max\{\beta(d(x, y))d(x, y), \beta(d(x, Tx))d(x, Tx), \beta(d(y, Ty))d(y, Ty), \beta(d(x, Ty))d(x, Ty), \beta(M(Tx, y))d(y, T$$

We extend this definition to Geraghty-Ciric fuzzy contraction mapping.

Definition 6. Let $(X, M, *)$ be a complete fuzzy metric space. The function $f: M \rightarrow M$ is said to be a Geraghty-Ciric fuzzy contraction if there exists $\beta \in S = \{R^+ \rightarrow [0, 1), \lim_{n \rightarrow \infty} \beta(s_n) = 1 \Rightarrow \lim_{n \rightarrow \infty} s_n = 0\}$ such that

$$\frac{1}{M(fx, fy, t)} - 1 \leq N(x, y)$$

for each $x, y \in X, t \in (0, \infty)$ and

$$N(x, y) = \max\left\{\beta\left(\frac{1}{M(x, y, t)} - 1\right)\left(\frac{1}{M(x, y, t)} - 1\right), \beta\left(\frac{1}{M(fx, y, t)} - 1\right)\left(\frac{1}{M(fx, y, t)} - 1\right), \beta\left(\frac{1}{M(x, fy, t)} - 1\right)\left(\frac{1}{M(x, fy, t)} - 1\right), \beta\left(\frac{1}{M(x, fx, t)} - 1\right)\left(\frac{1}{M(x, fx, t)} - 1\right), \beta\left(\frac{1}{M(y, fy, t)} - 1\right)\left(\frac{1}{M(y, fy, t)} - 1\right)\right\}$$

Definition 7. Let $(X, M, *)$ be a complete fuzzy metric space. A pair of mappings $f, g: X \rightarrow X$ is called a Geraghty-Ciric fuzzy couple if there exists $\beta \in S = \{R^+ \rightarrow [0, 1), \lim_{n \rightarrow \infty} \beta(s_n) = 1 \Rightarrow \lim_{n \rightarrow \infty} s_n = 0\}$ such that

$$\frac{1}{M(fx, gy, t)} - 1 \leq \tilde{N}(x, y).$$

for each $x, y \in X, t \in (0, \infty)$ and

$$\tilde{N}(x, y) = \max\left\{\beta\left(\frac{1}{M(x, y, t)} - 1\right)\left(\frac{1}{M(x, y, t)} - 1\right), \beta\left(\frac{1}{M(fx, y, t)} - 1\right)\left(\frac{1}{M(fx, y, t)} - 1\right), \beta\left(\frac{1}{M(x, gy, t)} - 1\right)\left(\frac{1}{M(x, gy, t)} - 1\right), \beta\left(\frac{1}{M(fx, x, t)} - 1\right)\left(\frac{1}{M(fx, x, t)} - 1\right), \beta\left(\frac{1}{M(y, gy, t)} - 1\right)\left(\frac{1}{M(y, gy, t)} - 1\right)\right\}$$

Results and Discussion

Theorem 1. Let $(X, M, *)$ be a complete fuzzy metric space and $f, g: X \rightarrow X$ a Geraghty-Ciric fuzzy couple. Then f, g have a unique fixed point in $(X, M, *)$.

Proof. Let $x_0 \in X$ be an arbitrary point in X . Putting $x_1 = f(x_0), x_2 = g(x_1), x_3 = f(x_2), \dots, x_{2n+1} = f(x_{2n}), x_{2n+2} = g(x_{2n+1})$, and so on, we construct a sequence $\{x_{2n}\}_{n \in \mathbb{N}}$.

Firstly, we show that the sequence

$$P_n = \max\left\{\frac{1}{M(x_{2k+1}, x_{2s+2}, t)} - 1, 0 \leq k, s \leq n, k, s \in \mathbb{N} \cup \{0\}, t > 0\right\} \text{ is bounded in } X.$$

Indeed, taking $n \in \mathbb{N}$ and $1 \leq k, s \leq n$ we have

$$\begin{aligned} \frac{1}{M(x_{2k+1}, x_{2s+2}, t)} - 1 &= \frac{1}{M(fx_{2k}, gx_{2s+1}, t)} - 1 \leq \tilde{N}(x_{2k}, x_{2s+1}) = \max\left\{\beta\left(\frac{1}{M(x_{2k}, x_{2s+1}, t)} - 1\right)\left(\frac{1}{M(x_{2k}, x_{2s+1}, t)} - 1\right), \right. \\ &\beta\left(\frac{1}{M(x_{2k+1}, x_{2s+1}, t)} - 1\right)\left(\frac{1}{M(x_{2k+1}, x_{2s+1}, t)} - 1\right), \beta\left(\frac{1}{M(x_{2k}, x_{2s+2}, t)} - 1\right)\left(\frac{1}{M(x_{2k}, x_{2s+2}, t)} - 1\right), \beta\left(\frac{1}{M(x_{2k+1}, x_{2s}, t)} - 1\right)\left(\frac{1}{M(x_{2k+1}, x_{2s}, t)} - 1\right), \\ &\beta\left(\frac{1}{M(x_{2s+2}, x_{2s+1}, t)} - 1\right)\left(\frac{1}{M(x_{2s+2}, x_{2s+1}, t)} - 1\right)\left.\right\} < \max\left\{\frac{1}{M(x_{2k}, x_{2s+1}, t)} - 1, \right. \\ &\left.\frac{1}{M(x_{2k+1}, x_{2s+1}, t)} - 1, \frac{1}{M(x_{2k}, x_{2s+2}, t)} - 1, \frac{1}{M(x_{2k+1}, x_{2s}, t)} - 1, \frac{1}{M(x_{2s+2}, x_{2s+1}, t)} - 1\right\} \leq P_n \end{aligned}$$

Consequently, $\max \left\{ \left(\frac{1}{M(x_{2k+1}, x_{2s+2}, t)} - 1 \right), 0 \leq k, s \leq n \right\} < P_n$

As a result, there is $r_n, 1 \leq r_n \leq n$ such that

$$P_n = \frac{1}{M(x_0, x_{2r_n+2}, t)} - 1$$

We have that $0 \leq P_{n-1} \leq P_n$. So the sequence $\{P_n\}_{n \in \mathbb{N}}$ is non-decreasing.

Let us show that this sequence is also bounded.

Suppose that the sequence $\{P_n\}_{n \in \mathbb{N}}$ is unbounded. As a result, since it is increasing, we have

$$\lim_{n \rightarrow \infty} P_n = +\infty$$

Since the fuzzy space is triangular, we have

$$P_n = \frac{1}{M(x_0, x_{2r_n+2}, t)} - 1 \leq \frac{1}{M(x_0, x_1, t)} - 1 + \frac{1}{M(x_1, x_{2r_n+2}, t)} - 1 \leq \frac{1}{M(x_0, x_1, t)} - 1 + \tilde{N}(x_0, x_{2r_n+2})$$

Such that

$$\begin{aligned} \tilde{N}(x_0, x_{2r_n+2}) = \max \left\{ \beta \left(\frac{1}{M(x_0, x_{2r_n+1}, t)} - 1 \right) \left(\frac{1}{M(x_0, x_{2r_n+1}, t)} - 1 \right), \beta \left(\frac{1}{M(x_1, x_{2r_n+1}, t)} - 1 \right) \left(\frac{1}{M(x_1, x_{2r_n+1}, t)} - 1 \right), \right. \\ \left. \beta \left(\frac{1}{M(x_0, x_{2r_n+2}, t)} - 1 \right) \left(\frac{1}{M(x_0, x_{2r_n+2}, t)} - 1 \right), \beta \left(\frac{1}{M(x_0, x_1, t)} - 1 \right) \left(\frac{1}{M(x_1, x_0, t)} - 1 \right), \beta \left(\frac{1}{M(x_{2r_n+2}, x_{2r_n+1}, t)} - 1 \right) \frac{1}{M(x_{2r_n+2}, x_{2r_n+1}, t)} - 1 \right\} \end{aligned}$$

Depending on the above inequality, we consider the following cases.

Case 1. We take $\tilde{N}(x_0, x_{2r_n+2}) = \beta \left(\frac{1}{M(x_0, x_{2r_n+1}, t)} - 1 \right) \cdot \left(\frac{1}{M(x_0, x_{2r_n+1}, t)} - 1 \right)$. By replacing this expression, we have

$$\frac{1}{M(x_0, x_{2r_n+2}, t)} - 1 \leq \frac{1}{M(x_0, x_1, t)} - 1 + \beta \left(\frac{1}{M(x_0, x_{2r_n+1}, t)} - 1 \right) \cdot \left(\frac{1}{M(x_0, x_{2r_n+1}, t)} - 1 \right)$$

$$P_n < \frac{1}{M(x_0, x_1, t)} - 1 + \beta \left(\frac{1}{M(x_0, x_{2r_n+1}, t)} - 1 \right) \cdot P_n$$

$$\frac{1 - \left(\frac{1}{M(x_0, x_1, t)} - P_n \right)}{P_n} \leq \beta \left(\frac{1}{M(x_0, x_{2r_n+1}, t)} - 1 \right) < 1$$

$$1 - \frac{\left(\frac{1}{M(x_0, x_1, t)} - 1 \right)}{P_n} \leq \beta \left(\frac{1}{M(x_0, x_{2r_n+1}, t)} - 1 \right) < 1$$

Taking the limit $\lim_{n \rightarrow \infty} 1 - \frac{\left(\frac{1}{M(x_0, x_1, t)} - 1 \right)}{P_n} = 1$, we have $\lim_{n \rightarrow \infty} \beta \left(\frac{1}{M(x_0, x_{2r_n+1}, t)} - 1 \right) = 1$ and

$$\lim_{n \rightarrow \infty} \frac{1}{M(x_0, x_{2r_n+1}, t)} - 1 = 0$$

Consequently $\lim_{n \rightarrow \infty} P_n = \frac{1}{M(x_0, x_1, t)} - 1$ which is a contradiction because $\lim_{n \rightarrow \infty} P_n = +\infty$.

Case 2. If we choose $\tilde{N}(x_0, x_{2r_n+2}) = \beta \left(\frac{1}{M(x_1, x_{2r_n+1}, t)} - 1 \right) \left(\frac{1}{M(x_1, x_{2r_n+1}, t)} - 1 \right)$

$$P_n \leq \frac{1}{M(x_0, x_1, t)} - 1 + \beta \left(\frac{1}{M(x_1, x_{2r_n+1}, t)} - 1 \right) \left(\frac{1}{M(x_1, x_{2r_n+1}, t)} - 1 \right)$$

$$P_n < \frac{1}{M(x_0, x_1, t)} - 1 + \beta \left(\frac{1}{M(x_0, x_{2r_n+1}, t)} - 1 \right) \cdot P_n$$

$$\frac{1 - \left(\frac{1}{M(x_0, x_1, t)} - P_n \right)}{P_n} \leq \beta \left(\frac{1}{M(x_1, x_{2r_n+1}, t)} - 1 \right) < 1$$

$$1 - \frac{\left(\frac{1}{M(x_0, x_1, t)} - 1 \right)}{P_n} \leq \beta \left(\frac{1}{M(x_1, x_{2r_n+1}, t)} - 1 \right) < 1$$

Knowing that $\lim_{n \rightarrow \infty} 1 - \frac{\left(\frac{1}{M(x_0, x_1, t)} - 1 \right)}{P_n} = 1$, it results $\lim_{n \rightarrow \infty} \beta \left(\frac{1}{M(x_1, x_{2r_n+1}, t)} - 1 \right) = 1$ and $\lim_{n \rightarrow \infty} \frac{1}{M(x_1, x_{2r_n+1}, t)} - 1 = 0$

So $\lim_{n \rightarrow \infty} P_n = \frac{1}{M(x_0, x_1, t)} - 1$ which is a contradiction because $\lim_{n \rightarrow \infty} P_n = +\infty$.

Case 3. In this case, we take $\tilde{N}(x_0, x_{2r_n+2}) = \beta \left(\frac{1}{M(x_0, x_{2r_n+2}, t)} - 1 \right) \left(\frac{1}{M(x_0, x_{2r_n+2}, t)} - 1 \right)$

$$P_n \leq \frac{1}{M(x_0, x_1, t)} - 1 + \beta \left(\frac{1}{M(x_0, x_{2r_n+2}, t)} - 1 \right) \cdot \left(\frac{1}{M(x_0, x_{2r_n+2}, t)} - 1 \right)$$

$$P_n < \frac{1}{M(x_0, x_1, t)} - 1 + \beta \left(\frac{1}{M(x_0, x_{2r_n+2}, t)} - 1 \right) \cdot P_n$$

From the above inequality, we have $1 - \frac{\left(\frac{1}{M(x_0, x_1, t)} - 1 \right)}{P_n} \leq \beta \left(\frac{1}{M(x_0, x_{2r_n+2}, t)} - 1 \right) < 1$.

Taking the limit of three sides and using squeezing theorem, it yields $\lim_{n \rightarrow \infty} \beta \left(\frac{1}{M(x_0, x_{2r_n+2}, t)} - 1 \right) = 1$ and $\lim_{n \rightarrow \infty} \frac{1}{M(x_0, x_{2r_n+2}, t)} - 1 = 0$.

This leads to $\lim_{n \rightarrow \infty} P_n = \frac{1}{M(x_0, x_1, t)} - 1$ which contradicts our assumption.

Case 4. Taking now $\tilde{N}(x_0, x_{2r_n+2}) = \beta \left(\frac{1}{M(x_0, x_1, t)} - 1 \right) \left(\frac{1}{M(x_1, x_0, t)} - 1 \right)$

we have

$$P_n \leq \frac{1}{M(x_0, x_1, t)} - 1 + \beta \left(\frac{1}{M(x_0, x_1, t)} - 1 \right) \cdot \left(\frac{1}{M(x_0, x_1, t)} - 1 \right) \leq 2 \left(\frac{1}{M(x_0, x_1, t)} - 1 \right)$$

Which proves that the sequence $\{P_n\}$ is not bounded.

Case 5. Studying $\tilde{N}(x_0, x_{2r_n+2}) = \beta \left(\frac{1}{M(x_{2r_n+2}, x_{2r_n+1}, t)} - 1 \right) \left(\frac{1}{M(x_{2r_n+2}, x_{2r_n+1}, t)} - 1 \right)$

we take

$$P_n \leq \frac{1}{M(x_0, x_1, t)} - 1 + \beta \left(\frac{1}{M(x_{2r_n+2}, x_{2r_n+1}, t)} - 1 \right) \left(\frac{1}{M(x_{2r_n+2}, x_{2r_n+1}, t)} - 1 \right)$$

$$P_n < \frac{1}{M(x_0, x_1, t)} - 1 + \beta \left(\frac{1}{M(x_{2r_n+2}, x_{2r_n+1}, t)} - 1 \right) \cdot P_n$$

$$\text{Calculating, we have } 1 - \frac{\left(\frac{1}{M(x_0, x_1, t)} - 1 \right)}{P_n} \leq \beta \left(\frac{1}{M(x_{2r_n+2}, x_{2r_n+1}, t)} - 1 \right) < 1$$

By taking limits in the above inequality, it yields $\lim_{n \rightarrow \infty} \beta \left(\frac{1}{M(x_{2r_n+2}, x_{2r_n+1}, t)} - 1 \right) = 1$ and $\lim_{n \rightarrow \infty} \left(\frac{1}{M(x_{2r_n+2}, x_{2r_n+1}, t)} - 1 \right) = 0$.

Consequently $\lim_{n \rightarrow \infty} P_n = \frac{1}{M(x_0, x_1, t)} - 1$ which is a contradiction.

Since we achieve a contradiction in all cases, we have that the sequence $\{P_n\}_{n \in \mathbb{N}}$ is bounded.

The sequence $\{P_n\}_{n \in \mathbb{N}}$ is increasing and bounded from above, as a result, it converges.

Constructing the sequence $q_n = \sup \left\{ \frac{1}{M(x_k, x_s, t)} - 1, k, s \geq n, k, s \in \mathbb{N} \right\}$

We have that $0 \leq q_n \leq q_{n-1} \leq \dots \leq q_0 \leq \lim_{n \rightarrow \infty} P_n \leq q$

Since the sequence $\{q_n\}_{n \in \mathbb{N}}$ is decreasing and bounded from below, it converges to $q \geq 0$.

Let us prove that $q = 0$.

Suppose that $q > 0$.

We see the following inequality

$$\begin{aligned} & \frac{1}{M(x_{2k+1}, x_{2s+2}, t)} - 1 \\ & \leq \max \left\{ \beta \left(\frac{1}{M(x_{2k}, x_{2s+1}, t)} - 1 \right) \left(\frac{1}{M(x_{2k}, x_{2s+1}, t)} - 1 \right), \right. \\ & \quad \beta \left(\frac{1}{M(x_{2k+1}, x_{2s+1}, t)} - 1 \right) \left(\frac{1}{M(x_{2k+1}, x_{2s+1}, t)} - 1 \right), \\ & \quad \beta \left(\frac{1}{M(x_{2k}, x_{2s+2}, t)} - 1 \right) \left(\frac{1}{M(x_{2k}, x_{2s+2}, t)} - 1 \right), \\ & \quad \beta \left(\frac{1}{M(x_{2k}, x_{2s+1}, t)} - 1 \right) \left(\frac{1}{M(x_{2k}, x_{2s+1}, t)} - 1 \right), \\ & \quad \left. \beta \left(\frac{1}{M(x_{2s+1}, x_{2s+1}, t)} - 1 \right) \left(\frac{1}{M(x_{2s+1}, x_{2s+1}, t)} - 1 \right) \right\} \end{aligned}$$

Analysing the cases we have:

Case 1.

$$\frac{1}{M(x_{2k+1}, x_{2s+2}, t)} - 1 \leq \beta \left(\frac{1}{M(x_{2k}, x_{2s+1}, t)} - 1 \right) \left(\frac{1}{M(x_{2k}, x_{2s+1}, t)} - 1 \right),$$

Taking the limit when $k, s \rightarrow \infty, t > 0$, of the supremum of both sides, we have

$$q \leq \lim_{k,s \rightarrow +\infty} \sup \beta \left(\frac{1}{M(x_{2k}, x_{2s+1}, t)} - 1 \right) \cdot q$$

As a result, $\lim_{k,s \rightarrow +\infty} \sup \beta \left(\frac{1}{M(x_{2k}, x_{2s+1}, t)} - 1 \right) = 1$ and consequently $\lim_{k,s \rightarrow +\infty} \frac{1}{M(x_{2k}, x_{2s+1}, t)} - 1 = r = 0$

Using the same method, we can prove that $q = 0$ in all cases.

Since $\lim_{k,s \rightarrow +\infty} \frac{1}{M(x_{2k+1}, x_{2s+2}, t)} - 1 = 0$, the sequence $\{x_{2n}\}_{n \in \mathbb{N}}$ is Cauchy.

From the completeness of the fuzzy space $(X, M, *)$ we have that the sequence $\{x_{2n}\}_{n \in \mathbb{N}}$ converges to a point $x \in M$.

Next, we have to prove that x is a common fixed point of f and g .

$$\begin{aligned} \frac{1}{M(x_{2n+1}, f x^*, t)} - 1 &= \frac{1}{M(g x_{2n}, f x^*, t)} - 1 \leq \max \left\{ \beta \left(\frac{1}{M(x_{2n}, x^*, t)} - 1 \right) \left(\frac{1}{M(x_{2n}, x^*, t)} - 1 \right), \beta \left(\frac{1}{M(g x_{2n}, x_{2n}, t)} - 1 \right) \left(\frac{1}{M(g x_{2n}, x_{2n}, t)} - 1 \right), \right. \\ &\quad \left. \beta \left(\frac{1}{M(f x^*, x^*, t)} - 1 \right) \left(\frac{1}{M(f x^*, x^*, t)} - 1 \right), \beta \left(\frac{1}{M(x_{2n+1}, x^*, t)} - 1 \right) \left(\frac{1}{M(x_{2n+1}, x^*, t)} - 1 \right), \right. \\ &\quad \left. \beta \left(\frac{1}{M(f x^*, x_{2n}, t)} - 1 \right) \left(\frac{1}{M(f x^*, x_{2n}, t)} - 1 \right) \right\} \end{aligned}$$

Let us discuss the following cases:

Case 1. Taking

$$\frac{1}{M(x_{2n+1}, f x^*, t)} - 1 \leq \beta \left(\frac{1}{M(x_{2n}, x^*, t)} - 1 \right) \cdot \left(\frac{1}{M(x_{2n}, x^*, t)} - 1 \right)$$

we see that

$$\frac{1}{M(x^*, f x^*, t)} - 1 \leq \frac{1}{M(x^*, x_{2n+1}, t)} - 1 + \frac{1}{M(x_{2n+1}, f x^*, t)} - 1 \leq \frac{1}{M(x^*, x_{2n+1}, t)} - 1 + \beta \left(\frac{1}{M(x_{2n}, x^*, t)} - 1 \right) \cdot \left(\frac{1}{M(x_{2n}, x^*, t)} - 1 \right)$$

Considering the limit of the inequality, we get

$$0 \leq \frac{1}{M(x^*, f x^*, t)} - 1 \leq \lim_{n \rightarrow \infty} \frac{1}{M(x_{2n+1}, f x^*, t)} - 1 \leq 0$$

So $\frac{1}{M(x^*, f x^*, t)} - 1 = 0$ and $M(x^*, f x^*, t) = 1$ and $f x^* = x^*$

Using the same method, we prove that $g x^* = x^*$

So $f x^* = g x^* = x^*$ and x^* is a common fixed point for f and g .

Let us prove that x^* is unique.

Suppose that there exists another point y^* such that

$$f y^* = g y^* = y^*$$

$$\begin{aligned} \frac{1}{M(x^*, y^*, t)} - 1 &= \frac{1}{M(fx^*, gy^*, t)} - 1 \leq \beta \left(\frac{1}{M(x^*, y^*, t)} - 1 \right) \max \left\{ \beta \left(\frac{1}{M(x^*, y^*, t)} - 1 \right) \left(\frac{1}{M(x^*, y^*, t)} - 1 \right), \beta \left(\frac{1}{M(fx^*, y^*, t)} - 1 \right) \left(\frac{1}{M(fx^*, y^*, t)} - 1 \right), \beta \left(\frac{1}{M(x^*, gy^*, t)} - 1 \right) \left(\frac{1}{M(x^*, gy^*, t)} - 1 \right), \beta \left(\frac{1}{M(x^*, fx^*, t)} - 1 \right) \left(\frac{1}{M(x^*, fx^*, t)} - 1 \right), \beta \left(\frac{1}{M(y^*, gy^*, t)} - 1 \right) \left(\frac{1}{M(y^*, gy^*, t)} - 1 \right) \right\} \\ &= \beta \left(\frac{1}{M(x^*, y^*, t)} - 1 \right) \cdot \left(\frac{1}{M(x^*, y^*, t)} - 1 \right) \\ \left(\frac{1}{M(x^*, y^*, t)} - 1 \right) &\leq \beta \left(\frac{1}{M(x^*, y^*, t)} - 1 \right) \cdot \left(\frac{1}{M(x^*, y^*, t)} - 1 \right) \end{aligned}$$

which holds only for $\frac{1}{M(x^*, y^*, t)} - 1 = 0$ since $\beta \left(\frac{1}{M(x^*, y^*, t)} - 1 \right) < 1$

Example 2

Let $X = R^+, t > 0$, is continuous

$$M: X \times X \times (0, +\infty) \rightarrow [0, 1] \quad M(x, y, t) = \frac{t}{t + |x - y|}$$

For every $x, y \in X, t > 0$, a fuzzy metric space. The triple $(X, M, *)$ is a fuzzy metric space, and it is complete and triangular.

$$\text{Let } f: X \rightarrow X, f(x) = \begin{cases} \frac{4}{5}, & x \neq 1 \\ 1, & x = 1 \end{cases} \quad g: X \rightarrow X \quad g(y) = \begin{cases} \frac{1}{5}, & x \neq 1 \\ 1, & x = 1 \end{cases}$$

be two functions, and

$$\beta(s) = \begin{cases} \frac{1}{s}, & 1 < s < \frac{5}{4} \\ \frac{9}{10}, & \text{otherwise} \end{cases}$$

We see that

$$\frac{1}{M(fx, gy, t)} - 1 \leq \max \left\{ \beta \left(\frac{1}{M(x, y, t)} - 1 \right) \left(\frac{1}{M(x, y, t)} - 1 \right), \beta \left(\frac{1}{M(fx, y, t)} - 1 \right) \left(\frac{1}{M(fx, y, t)} - 1 \right), \beta \left(\frac{1}{M(x, gy, t)} - 1 \right) \left(\frac{1}{M(x, gy, t)} - 1 \right), \beta \left(\frac{1}{M(x, fx, t)} - 1 \right) \left(\frac{1}{M(x, fx, t)} - 1 \right), \beta \left(\frac{1}{M(y, gy, t)} - 1 \right) \left(\frac{1}{M(y, gy, t)} - 1 \right) \right\}$$

Consequently, the functions f and g have a common fixed point

$$x = 1, f1 = g1 = 1.$$

Theorem 3. Let $(X, M, *)$ be a complete, triangular fuzzy metric space and $f: X \rightarrow X$ a Geraghty-Ciric fuzzy contraction function. Then f has a unique fixed point in X .

Proof. If we take $f = g$ in Theorem 3.1, our result is true.

Corollary 4. Let $(X, M, *)$ be a complete, triangular fuzzy metric space and $f: X \rightarrow X$ a Ciric fuzzy contraction function.

$$\frac{1}{M(fx, gy, t)} - 1 \leq k \max \left\{ \frac{1}{M(x, y, t)} - 1, \frac{1}{M(fx, y, t)} - 1, \frac{1}{M(x, fy, t)} - 1, \frac{1}{M(fx, x, t)} - 1, \frac{1}{M(y, y, t)} - 1 \right\}$$

For $0 < k < 1, x, y \in X, t > 0$.

Then f has a unique fixed point.

Conclusion

We investigated common fixed-point results for a pair of weakly compatible mappings satisfying a Geraghty-Cirić-type contraction condition in the setting of complete fuzzy metric spaces in this article. Using the properties of Cauchy and Convergent sequences, we proved the existence and uniqueness of common fixed point of the mappings under consideration. The results we get extend and generalise the existing theorems in the literature (especially that of Shu-Fang Li et al) with a view about weak compatibility and contractive condition in fuzzy metric spaces. This shows that how generalized contraction conditions are combined with the structure of fuzzy metric space is promising for further developments in fixed point theory. A relevant example has been given to validate the main theorem. A corollary and a special case of the main theorem are derived thus showing the strength of the said approach.

Recommendations

Based on the results obtained in this study, several directions for future research can be suggested. The proposed approach can be extended to more general classes of mappings, such as multivalued mappings, cyclic mappings, or mappings satisfying weaker compatibility conditions. Furthermore, it would be of interest to investigate similar fixed-point results in more generalized spaces, including intuitionistic fuzzy metric spaces, probabilistic metric spaces, or other hybrid structures that capture uncertainty in a more refined way. In addition, the methods developed in this work could be applied to problems in applied mathematics, such as integral equations, differential equations, and models involving uncertainty, where fuzzy metric frameworks are particularly well-suited.

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Author(s) Information

Eriola Sila

Department of Mathematics, Faculty of Natural Science,
University of Tirana, Bulevardi Zogu i Pare, 1057
Tirane, Albania,
ORCID iD: <https://orcid.org/0009-0005-3170-3678>
*Contact e-mail: eriola.sila@unitir.edu.al

Dritan Gerbeti

Department of Mathematics, Faculty of Natural Science,
University ‘Luigj Gurakuqi’, Sheshi “2 Prilli”, Shkodër,
Albania
ORCID iD: <https://orcid.org/0009-0005-1416-7850>

Silvana Liftaj

University of Aleksander Moisiu, Department of
Mathematics, Faculty of Information Technology,
Durrës, Albania
ORCID iD: <https://orcid.org/0009-0009-3688-5035>

*Corresponding author(s) contact email

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Matheuristics in Scheduling Problems: A Global Bibliometric Analysis

Kamil Colbay

Konya Technical University

Orhan Engin

Konya Technical University

Abstract: Matheuristic approaches, which seamlessly combine exact mathematical programming with heuristic algorithms, have gained significant momentum in solving complex, NP-hard scheduling problems. Despite their growing popularity and effectiveness, there is a notable lack of comprehensive bibliometric mapping in this specific subfield. This study conducts a quantitative bibliometric analysis to uncover the structural and dynamic characteristics of literature at the intersection of matheuristics and scheduling. A total of 370 peer-reviewed articles and conference papers, published between 2007 and 2025, were extracted from the Scopus database and analyzed using the bibliometrix R package. The findings reveal a steady, logarithmic increase in scientific production, driven by the demands of complex, large-scale industrial applications. Co-occurrence network analyses confirm that current research is heavily centered on the integration of Mixed-Integer Linear Programming (MILP) with heuristic frameworks. The analysis identifies critical research gaps, suggesting that future studies should focus on energy-efficient scheduling, dynamic environments with stochastic constraints, and algorithm hybridization with machine learning.

Keywords: Bibliometric analysis, Matheuristics, Scheduling, Science mapping, Mixed-integer linear programming

Introduction

Scheduling is the process of allocating limited resources to various tasks or operations in the most efficient manner, subject to specific constraints and within a given time frame. It plays a critical role in optimizing operational processes across many different industries, such as manufacturing, logistics, healthcare, and transportation. In complex production environments and Industry 4.0/5.0 applications, scheduling problems are inherently considered “NP-hard” from a combinatorial optimization perspective, making it extremely difficult to find the optimal production or service plan (Kriouich & Sarir, 2024).

Traditional exact methods, particularly approaches like MILP, while yielding optimal results for small-scale problems, face significant challenges in terms of scalability and computation time as problem size increases. On the other hand, while traditional heuristic and meta-heuristic methods can solve large problems within reasonable time frames, they cannot guarantee the discovery of the optimal solution (Ouhadi et al., 2024). To overcome the limitations of these two approaches, mathematical heuristics—or exact-heuristic hybrid methods—which combine the strengths of mathematical programming techniques with those of heuristic algorithms, have gained significant momentum in recent years (Sidki et al., 2025; Fanjul-Peyro et al., 2017).

Despite the effectiveness of matheuristic approaches in scheduling problems and their growing popularity, there is no comprehensive study mapping the development, knowledge structure, and research trends in this field. The aim of this study is to identify global trends, author-institution collaborations, and the conceptual framework of

the literature at the intersection of “matheuristics” and “scheduling” through a bibliometric analysis. The goal is to identify existing gaps in literature and provide researchers with a robust reference source for future studies.

A review of the literature in the field of scheduling reveals a large number of bibliometric analyses and systematic reviews focusing on specific problem types or solution methods. For example, Coelho et al. (2021) mapped the 30-year evolution of Flexible Job Shop Scheduling (FJSP) problems, while İnce et al. (2024) examined group scheduling problems in flow-shop workshops. Similarly, Merdane et al. (2025) investigated hybrid flow shop scheduling problems and Çölbay & Engin (2025) provided a bibliometric perspective on fuzzy-based hybrid flow shop with multiprocessor scheduling. Furthermore, Shargh et al. (2024) conducted a bibliometric analysis of scheduling problems in service systems. In addition, various scientific mapping studies addressing the applications of Artificial Intelligence (AI) and Constraint Programming (CP) in scheduling problems are available (Bahroun et al., 2023; Kriouich & Sarir, 2024; Prata et al., 2024).

When examining the literature regarding specific solution methods; in scheduling problems for independent parallel machines, in the routing and scheduling of home care services, and in the scheduling of battery-constrained Autonomous Guided Vehicles (AGVs), there are numerous highly cited original research articles reporting that mathematical programming approaches have been successfully applied and have demonstrated superior performance compared to traditional mathematical models (Fanjul-Peyro et al., 2017; Fikar & Hirsch, 2015; Singh et al., 2022).

However, in light of these detailed studies, although bibliometric analyses of specific algorithms, there is no bibliometric study in the literature that directly addresses the use of “matheuristics” methods in scheduling problems (Rahimi et al., 2022). This gap necessitates the development of a comprehensive academic profile for an extremely effective and emerging solution paradigm such as matheuristics. As the first bibliometric study in this specific subfield, the present work fills this significant gap in literature.

The remainder of this paper is organized as follows: Section 2 (Method) details the research methodology. Section 3 (Results and Discussion) presents the comprehensive results of the bibliometric analysis. Finally, Section 4 (Conclusion) concludes the study by summarizing the main findings and providing strategic recommendations for future research directions in the field of matheuristics and scheduling.

Method

In this study, a quantitative bibliometric analysis methodology was adopted to examine the structural and dynamic characteristics of scientific publications at the intersection of matheuristics and scheduling problems. Bibliometric analysis is a highly reliable method used to identify research trends, productivity, and conceptual networks through the statistical examination of quantitative data derived from scientific publications.

Data Collection and Search Policy

The research data was obtained from the Scopus database, which offers the broadest coverage in the fields of engineering and operations research and provides robust features for citation analysis. To fully capture the scope of the study, an advanced search query was created that includes mathematical heuristics (matheuristics, exact-heuristic, etc.) and basic scheduling terms (scheduling, job shop, flow shop, etc.). The search query used in the Scopus database is as follows:

TITLE-ABS-KEY ((“matheuristic*” OR “math-heuristic*” OR “hybrid mathematical programming” OR “MIP-based heuristic*” OR “exact-heuristic hybrid”) AND (“scheduling” OR “job shop” OR “flow shop” OR “open shop”)) AND PUBYEAR > 2006 AND PUBYEAR < 2026

Inclusion, Exclusion, and Data Cleaning Criteria

The search query above initially yielded 420 studies from the Scopus database. Strict exclusion criteria were applied to this raw dataset to ensure the maintenance of quality and focus. Only peer-reviewed research articles and conference papers were included in the analysis. Studies not directly related to the topic, book chapters, review articles, and editor’s notes were excluded. Following these filtering steps, a final set of 370 studies was identified for use in the analysis.

Data Analysis and Scientific Mapping Tools

Complete bibliographic metadata such as author names, affiliations, abstracts, keywords, and citation information for the 370 filtered studies were exported. The bibliometrix package, which is based on the open-source R programming language, and its no-code web interface, biblioshiny, were used for data performance analysis and scientific mapping. The resulting visual networks will shed light on the current state of the field as mapped by matheuristics algorithms and highlight potential future research areas.

Results and Discussion

An examination of the graph in Figure 1, which reflects the evolution of literature over time, reveals that academic interest in the application of matheuristic algorithms to scheduling problems has shown a steady upward trend, particularly in recent years. This growth is driven by the increasing need for these hybrid approaches in large-scale problems where traditional exact methods are constrained by solving time limits.

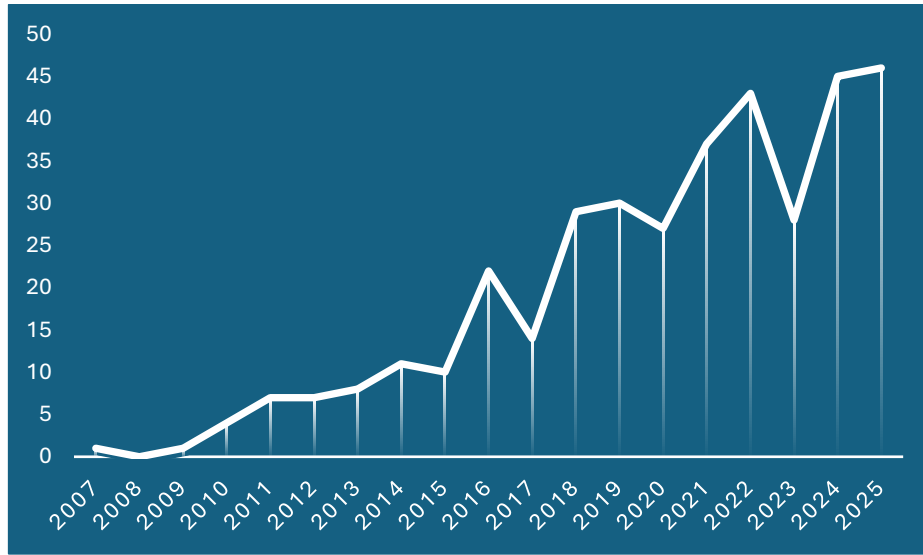


Figure 1. Annual scientific production

Figure 1 also shows a logarithmic growth trend, particularly in recent years. This can be attributed to the fact that the complex datasets generated by Industry 4.0/5.0 applications cannot be addressed using traditional methods, leading researchers to inevitably turn to hybrid (matheuristic) approaches. Figure 2 shows the journals where research is concentrated.

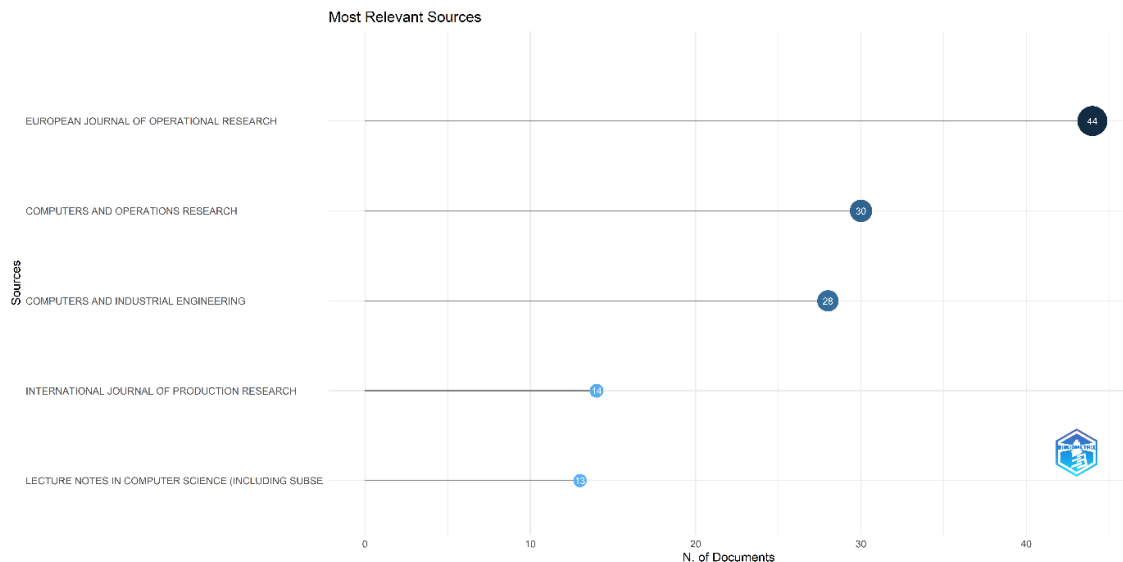


Figure 2. Most relevant sources

Figure 3 illustrates the journals with the highest citation counts within this dataset and demonstrates that prestigious journals in the fields of operations research and industrial engineering form the core of the field's knowledge base.

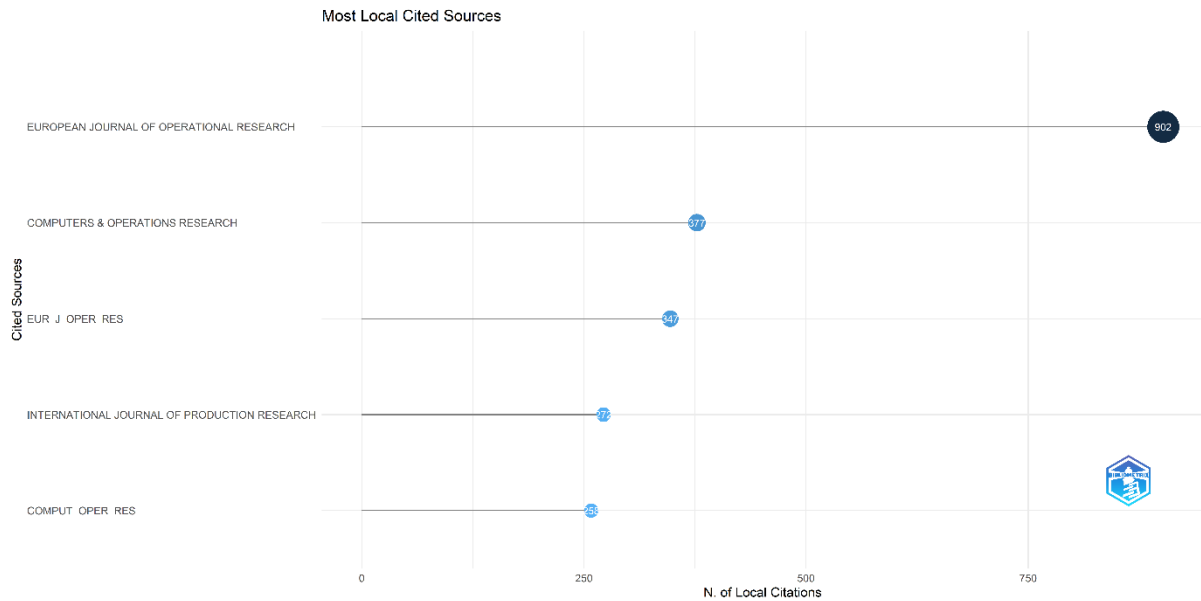


Figure 3. Most local cited sources

The fact that the European Journal of Operational Research (EJOR) and Computers & Operations Research are by far the leaders in both the number of publications and local citations in Figure 3, demonstrates that the theoretical and methodological foundations of this field are largely built upon publications in these prestigious journals. The fact that EJOR has achieved a very high citation count of 902 indicates that the benchmarks in the discipline originate from this journal.

The graph in Figure 4, which ranks the academic institutions with the highest number of publications in the field of matheuristics and scheduling, highlights which universities or research laboratories are leading the way in this specific subfield of optimization on a global scale.

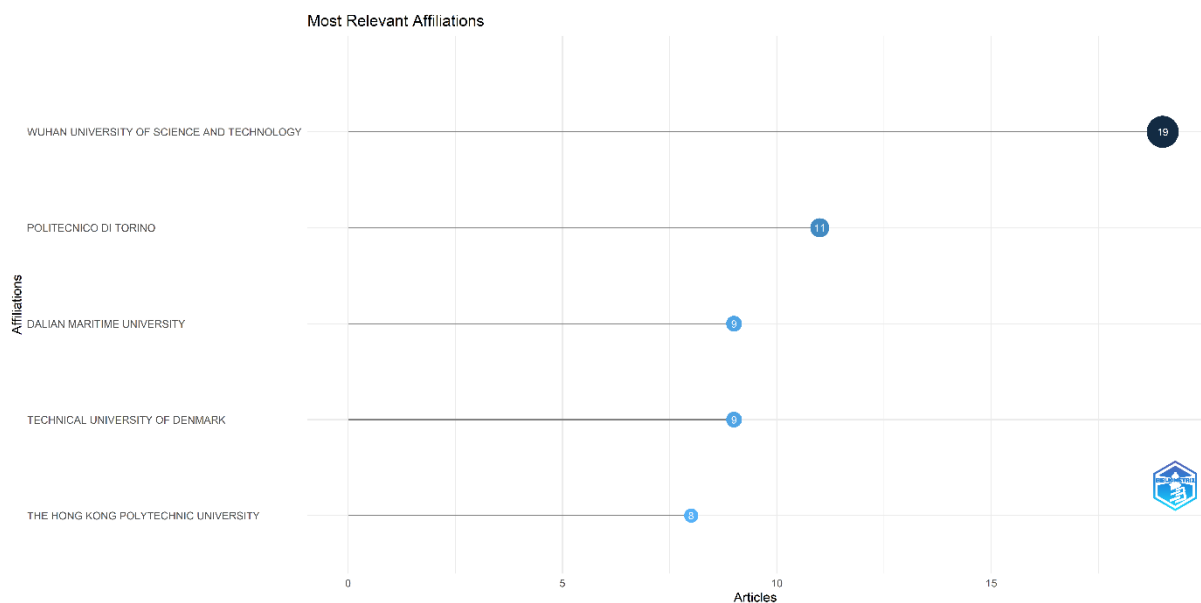


Figure 4. Most relevant affiliations

The prominence of institutions such as Wuhan University of Science and Technology and Dalian Maritime University in Figure 4, reflects the significant academic resources being invested in supply chain, maritime, and production planning optimization, particularly in the Asian region. The presence of Politecnico di Torino,

meanwhile, demonstrates that Europe continues to uphold its strong theoretical tradition in this field. The map in Figure 5 shows the distribution of countries based on their total number of publications.

Country Scientific Production

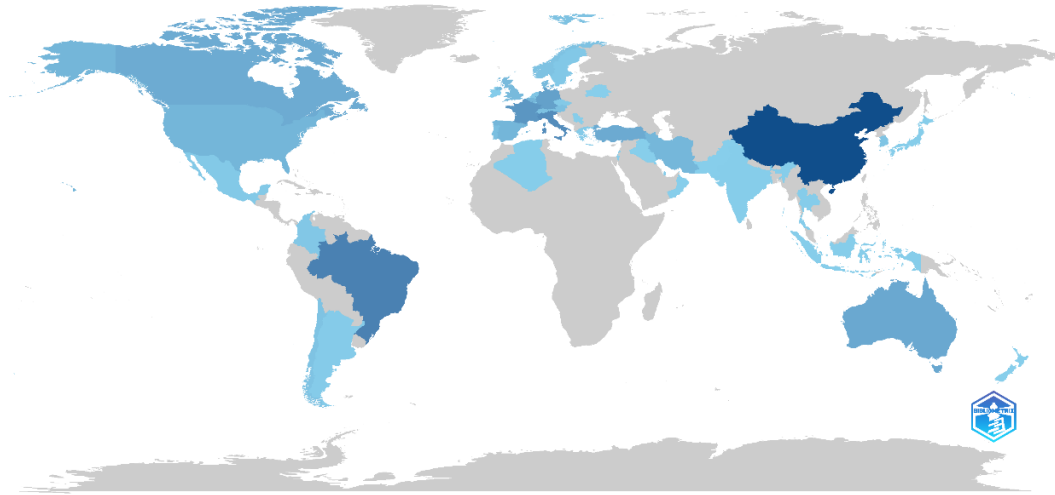


Figure 5. Country scientific production

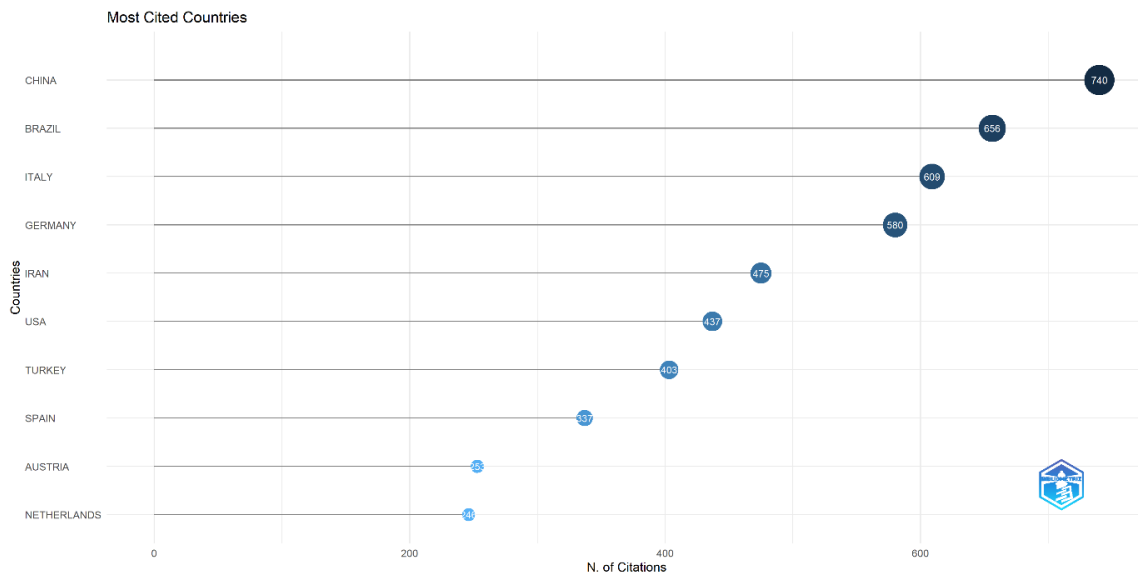


Figure 6. Most cited countries

Figure 6 illustrates countries' international impact and reveals that the matheuristics literature is geographically clustered in specific centers (particularly in countries with advanced industrial and technological infrastructure). It is evident that China holds a dominant position in terms of total publication output and the number of citations with 740. However, the fact that Brazil (656) and Italy (609) have also achieved very high citation counts demonstrates that these countries have developed highly effective and globally recognized solution approaches in the field of operations research. Turkey's ranking among the top countries with 403 citations underscores its potential to become a regional research hub.

Figure 7 reflects the concepts most frequently cited by authors. This word network provides a direct summary of the problem types in which algorithmic hybridizations are concentrated. It is quite significant that the concept of MILP occupies a central position among the keywords with 26 occurrences. This indicates that researchers have made it standard practice to establish hybrid architecture by integrating heuristic algorithms with powerful mathematical modeling tools such as MILP, rather than using them independently. Although a wide variety of scheduling problems exist, the keyword network implicitly reveals that research predominantly focuses on classic environments like flow-shop and parallel machine scheduling. Methodologically, integrating exact solvers with evolutionary or variable neighborhood search algorithms stands out as the most preferred matheuristic framework.

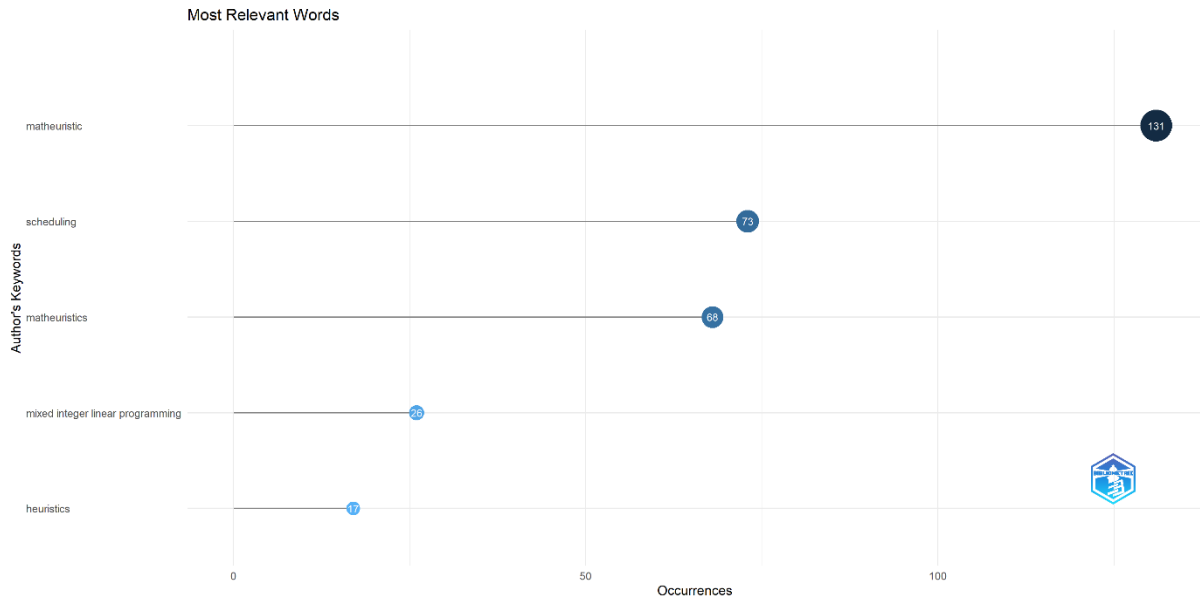


Figure 7. Most relevant words

Figure 8, which illustrates countries' tendencies toward joint publications and their international academic networks, maps the intensity and direction of the global collaborations established by researchers in this field of advanced optimization.

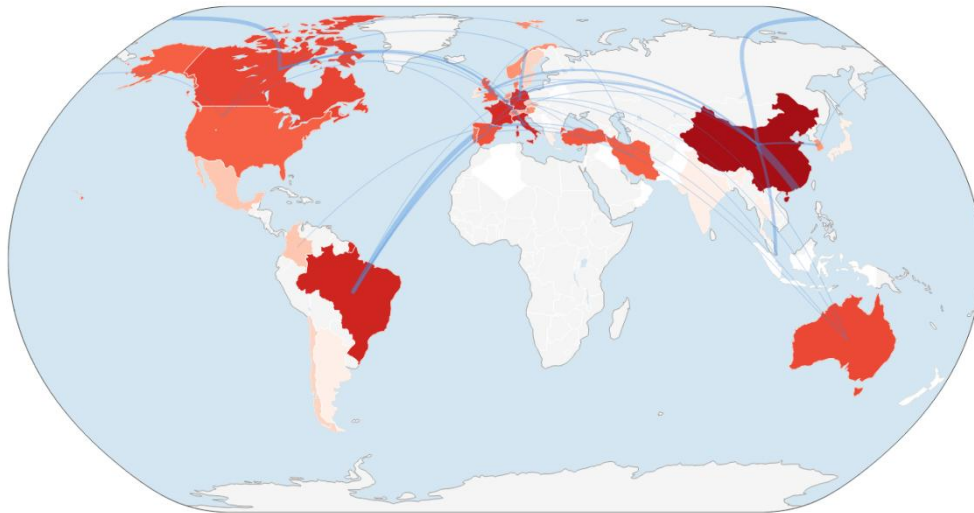


Figure 8. Countries' collaboration world map

The dark red areas and thick connecting lines on the map in Figure 8 demonstrate that the flow of information—particularly along the China-U.S.-Europe axis—serves as the main artery fueling this subdiscipline. This intense intercontinental academic traffic is an indication that matheuristics problems involve global-scale and universal industrial challenges.

Conclusion

In this study, a comprehensive bibliometric analysis was conducted on 370 articles at the intersection of scheduling problems and matheuristics, and the overall state of the literature was examined. Quantitative and visual findings demonstrate that matheuristic approaches, which combine the strengths of mathematical programming and heuristic methods, are increasingly becoming a dominant solution paradigm for solving complex and NP-hard scheduling problems. Data obtained from author, institutional, and country collaboration networks indicate that this field is characterized by an open and rapidly evolving structure driven by intensive global collaborations. Crucially, an analysis of the core keyword occurrences confirms that current research is heavily centered on the integration of "mixed integer linear programming" with heuristic frameworks, illustrating

that the literature is focusing on methodological hybridizations rather than being strictly limited to "makespan" minimization or specific classic problem sets.

Recommendations

In light of the bibliometric trends identified and the research gaps detected, the following recommendations are offered for future studies:

Filling Conceptual Gaps: In Figure 7, multi-objective mathematical heuristics models that address “energy-efficient scheduling” and “sustainability” objectives—currently viewed as niche or emerging fields—alongside classical optimization objectives (cost/time) should be prioritized. **Models for Dynamic and Uncertain Environments:** Most studies are based on static constraints. There is a need to develop robust matheuristics approaches enhanced with stochastic elements that address machine failures, order cancellations, or process duration uncertainties in real-world scenarios. **Hybridization with Machine Learning:** To enhance the efficiency of matheuristics methods and automate parameter optimization, new-generation intelligent solution architectures should be designed that integrate algorithms with machine learning techniques. **Expanding Global Collaborations:** In Figure 8, researchers in regions where the manufacturing sector is developing should be encouraged to conduct joint projects with leading institutions in the field (Figure 4). This will increase the number of universal case studies based on real Industry 4.0/5.0 datasets.

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Author(s) Information

Kamil Colbay

Konya Technical University
Akademi, Yeni İstanbul Street 363/6, 42250, Selçuklu,
Konya, Türkiye
ORCID iD: <https://orcid.org/0009-0001-7834-9179>
*Contact e-mail: kcolbay@ktun.edu.tr

Orhan Engin

Konya Technical University
Akademi, Yeni İstanbul Street 363/6, 42250, Selçuklu,
Konya, Türkiye
ORCID iD: <https://orcid.org/0000-0002-7250-0317>

*Corresponding author(s) contact email

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Solution of the Binary Knapsack Problem Using the Secretary Bird Optimization Algorithm

Vahit Tongur

Konya Technical University

Aysen Kucukyagliolu

Konya Technical University

Abstract: Many nature-inspired metaheuristic algorithms proposed in the literature are initially designed to operate in continuous search spaces. However, real-world problems are not limited to continuous domains; they also include discrete, combinatorial, and binary problem types. In this study, the performance of the Secretary Bird Optimization Algorithm (SBOA), a recently introduced metaheuristic method, is investigated on the knapsack problem, which belongs to the class of binary optimization problems. Numerous transfer functions have been proposed in the literature to transform continuous search spaces into binary ones. In this work, S-shaped transfer functions are employed for this purpose. Through this transformation, SBOA—originally designed for continuous domains—is adapted to the binary search space and referred to as the Binary SBOA (BSBOA). The performance of BSBOA is evaluated on well-known benchmark knapsack problem instances. While BSBOA achieves optimal solutions on 10 small-scale benchmark problems, it produces near-optimal results for 18 large-scale binary knapsack instances. This study aims to address the SBOA binary optimization problem and evaluate its performance in such an environment.

Keywords: Knapsack problem, Secretary bird optimization algorithm, Transfer functions

Introduction

The knapsack problem represents a classical discrete optimization framework frequently used to model various real-life decision-making scenarios. The goal is to identify a subset of items that yields the best possible objective value without violating predefined constraints. There are both single-dimensional and multi-dimensional variants of this problem. In the single-dimensional case, there is a single knapsack with a capacity limit into which the items are placed. In contrast, multi-dimensional variants may involve multiple knapsacks or multiple constraints associated with a single knapsack. In addition, some variants allow items to be selected more than once and included in the knapsack.

In this study, the single-dimensional version is considered. Each item is assumed to have a value and a weight, and the problem can be defined as selecting items to be placed into a single knapsack with a limited total weight capacity. Each item is associated with a weight (w) and a profit (p), which represents its level of utility. Let (C) denote the total weight capacity of the knapsack. In this case, the objective function of the problem can be formulated as given in Equation (1).

$$P_{max} = \sum_{i=1}^n p_i x_i \quad (1)$$

Subject to;

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$$\sum_{i=1}^n w_i x_i \leq C \quad (2)$$

Here, n denotes the number of items, p_i represents the profit of the i -th item, w_i denotes the weight of the i -th item, and x_i indicates whether the i -th item is included in the knapsack. If the i -th item is selected, then $x_i = 1$; otherwise, it takes the value 0. Accordingly, the problem considered in this study is referred to as the binary knapsack problem. Although the problem may appear simple, its complexity increases exponentially as the problem size grows. For this reason, it is classified as an NP-hard problem (Feng et al., 2015). For this reason, metaheuristic methods are more commonly preferred than exact methods, particularly for large-scale instances of the knapsack problem. The binary knapsack problem has been widely addressed in literature through various optimization techniques.

Wang et al. proposed an effective method for solving the multiple knapsack problem (MKP) by employing a discrete variant of differential evolution. In their approach, the MKP was formulated as an integer programming model compatible with discrete evolutionary strategies. Furthermore, a novel discretization mechanism was introduced, enabling the transformation of a continuous algorithm into a discrete one through the combined use of transfer functions and modular operations. To handle infeasible solutions, the GROA algorithm was incorporated. The proposed framework, which integrates multiple types of transfer functions such as S, V, U, and taper-shaped functions, was tested on 30 benchmark datasets (Wang et al., 2024).

Feng and Wang adapted the moth search algorithm to the binary domain and introduced a self-learning-based binary moth search method. This approach enhances population diversity and strengthens global search capability. A key component of the method is the self-learning straight-flight operator, which allows individuals to learn not only from the global best solution but also from better-performing individuals within the population. The performance of the proposed method was evaluated using 89 benchmark problems, and the impact of transfer functions on the algorithm's effectiveness was also analyzed. (Feng & Wang, 2022).

Li et al. proposed a binary version of the quantum-behaved particle swarm optimization algorithm to solve knapsack problems. Although the original method is known for its simplicity and strong global search ability, it suffers from premature convergence caused by particle clustering. To overcome this limitation, an improved variant was developed. In this enhanced version, a mapping mechanism based on the mean best position was introduced to address discretization challenges. Additionally, transfer functions were used to convert local attractors into binary representations, and crossover operations were applied to guide the search process. A repair mechanism and a diversity preservation strategy were also incorporated to prevent convergence to local optima and improve overall performance (Li et al., 2023).

Ali et al. introduced a modified differential evolution algorithm tailored for binary optimization problems. Their method enhances the classical differential evolution approach by incorporating new components such as solution encoding schemes, mapping strategies, and mechanisms to maintain population diversity. Moreover, an efficient fitness evaluation procedure was designed to both assess and repair candidate solutions. The effectiveness of the proposed method was validated on four datasets containing a total of 44 binary knapsack instances (Ali et al., 2021).

Abdel-Basset et al. developed a binary version of the slime mould algorithm for solving multidimensional knapsack problems. To enable the algorithm to operate in a binary search space, different categories of transfer functions, including S-shaped, V-shaped, and U-shaped functions, were investigated. However, the algorithm was observed to suffer from premature convergence. To address this issue, two improvement strategies were introduced. The first strategy involves modifying the current best solution by replacing an unselected item and evaluating the resulting solution. The second strategy focuses on restarting the population after a predefined number of iterations. These enhancements led to the development of an improved version of the algorithm. In addition, a repair mechanism was implemented to handle infeasible solutions (Abdel-Basset et al., 2021).

Gupta et al. proposed an improved sine-cosine algorithm by integrating it with differential evolution. In this hybrid approach, the search process dynamically switches between the modified sine-cosine mechanism and differential evolution based on the evolutionary state of the population. While the modified sine-cosine component improves exploitation and accelerates convergence, differential evolution contributes to maintaining population diversity and avoiding local optima. The parameters of the algorithm are adaptively controlled to achieve a balance between exploration and exploitation. A binary version of this method was also developed and applied to multidimensional knapsack problems, demonstrating competitive performance (Gupta et al., 2022).

Granmo et al. explored the application of the knapsack problem in real-world scenarios, particularly in the context of web resource allocation, and reported successful outcomes (Granmo et al., 2007).

Kong et al. introduced a binary and colony optimization approach for solving the multidimensional knapsack problem. Their method employs a pheromone update mechanism specifically designed for binary representations and allows the generation of infeasible solutions during the construction phase. To address this issue, a problem-specific repair operator was used to correct infeasible solutions at each iteration. Additionally, strategies such as pheromone reinitialization and alternative intensification mechanisms were implemented to reduce the risk of premature convergence (Kong et al., 2008). Tongur and Ülker adapted the migrating birds optimization algorithm to the knapsack problem by modifying its neighborhood structure to suit discrete search spaces. Their approach demonstrated promising performance on benchmark problems (Tongur & Ülker, 2017).

A general observation from the literature is that algorithms originally designed for continuous search spaces are commonly adapted to binary domains through the use of transfer functions. However, the effectiveness of these functions varies depending on the algorithm, yielding different levels of performance across studies. In this study, the performance of the SBOA, a recently proposed algorithm designed for continuous search spaces, is investigated in a binary setting by employing an S-shaped transfer function. The evaluation is conducted on the single-dimensional binary knapsack problem.

Method

Secretary Bird Optimization Algorithm (SBOA)

The Secretary Bird Optimization Algorithm (SBOA) is a recently developed metaheuristic approach inspired by the hunting behavior and survival strategies of secretary birds (Fu et al., 2024). The algorithm models both the preparation and hunting processes of the bird, mapping these natural behaviors into exploration and exploitation mechanisms within the optimization framework. The initial preparation phase of the bird corresponds to the initialization stage of the algorithm, while the subsequent hunting process is divided into multiple exploration phases. In contrast, the bird's predator avoidance strategies are associated with the exploitation phase of the algorithm.

Initial Phase

SBOA is a population-based optimization technique in which each individual represents a candidate solution within the search space. The position of each individual corresponds to the values of the decision variables of the problem. At the beginning of the algorithm, the positions of individuals are randomly generated according to Equation (3). Following initialization, the entire population is represented as given in Equation (4), where each row corresponds to a candidate solution.

$$X_{i,j} = lwb_j + r \times (upb_j - lwb_j), i = 1, 2, \dots, N, j = 1, 2, \dots, Dim \quad (3)$$

where, $X_{i,j}$ denotes the position of the bird, while lwb_j and upb_j represent the lower and upper bounds of the search space, respectively. The parameter r is a random number in the interval $[0,1]$.

$$X = \begin{bmatrix} x_{1,1} & x_{1,2} & \dots & x_{1,j} & \dots & x_{1,Dim} \\ x_{2,1} & x_{2,2} & \dots & x_{2,j} & \dots & x_{2,Dim} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{i,1} & x_{i,2} & \dots & x_{i,j} & \dots & x_{i,Dim} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{N,1} & x_{N,2} & \dots & x_{N,j} & \dots & x_{N,Dim} \end{bmatrix}_{N \times Dim} \quad (4)$$

where, X represents the entire population, while X_i denotes the i -th individual in the population. The term $X_{i,j}$ corresponds to the value of the j -th decision variable of the i -th individual. N , denotes the population size, and Dim represents the problem dimension.

Each individual in the population is evaluated using the objective function, and the corresponding fitness values are stored in a vector as described in Equation (5). These values are used to guide the search process throughout the optimization.

$$F = \begin{bmatrix} F_1 \\ \vdots \\ F_i \\ \vdots \\ F_N \end{bmatrix}_{N \times 1} = \begin{bmatrix} F(X_1) \\ \vdots \\ F(X_i) \\ \vdots \\ F(X_N) \end{bmatrix}_{N \times 1} \quad (5)$$

Where, F represents the objective function vector, while F_i denotes the objective function value of the i -th individual.

The SBOA updates individuals in the population based on two fundamental behavioral patterns observed in secretary birds:

- Hunting behavior
- Escape behavior

During each iteration, all individuals are updated according to these two mechanisms.

Hunting-Based Exploration Mechanism

The hunting behavior of secretary birds can be characterized by a three-stage process: detecting the prey, exhausting it, and finally attacking. In SBOA, these stages are modeled as three distinct phases of exploration. These stages are presented in Figure 1.

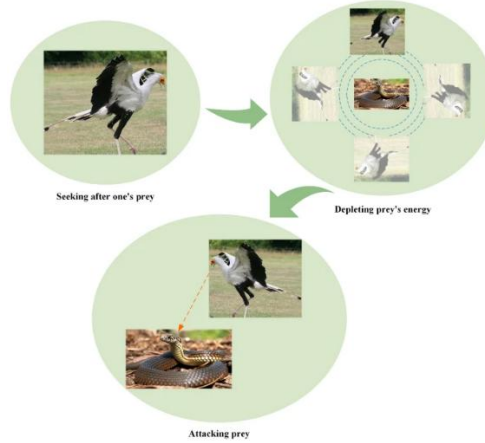


Figure 1. Hunting behaviors of secretary birds (Fu et al., 2024)

The entire search process is divided into three-time intervals, allowing the algorithm to gradually transition from exploration to exploitation.

Prey Searching (Phase 1): In the early stages of the optimization process, exploration is emphasized to ensure a broad search of the solution space. To achieve this, a differential evolution-based mechanism is incorporated. This mechanism generates new candidate solutions by exploiting the differences between randomly selected individuals. As a result, population diversity is increased, and the algorithm is encouraged to explore different regions of the search space. This enhances the probability of discovering high-quality solutions. The position update in this phase is performed according to Equations (6) and (7).

$$t < \frac{1}{3}T, x_{i,j}^{newP1} = x_{i,j} + (x_{random1} - x_{random2}) \times R_1 \quad (6)$$

$$X_i = \begin{cases} X_i^{new,P1}, & \text{if } F_i^{new,P1} < F_i \\ X_i, & \text{otherwise} \end{cases} \quad (7)$$

where, t refers to the current iteration, while T denotes the maximum number of iterations. The term $X_i^{new,P1}$ represents the updated position of the i -th individual during the first phase. In this stage, $x_{random1}$ and $x_{random2}$ correspond to randomly chosen candidate solutions. Additionally, R_i is a randomly generated value within the interval $[0,1]$, and Dim indicates the dimensionality of the search space.

Furthermore, $x_{i,j}^{newP1}$ corresponds to the value of the j -th decision variable of the i -th bird in the first phase, and $F_{i,j}^{newP1}$ represents the corresponding fitness value of the objective function.

Prey Exhaustion (Phase 2): After detecting the prey, the secretary bird attempts to weaken it through continuous movement and interaction. This behavior is modeled using stochastic movements based on Brownian motion. The incorporation of Brownian motion introduces randomness into the search process, which helps the algorithm avoid premature convergence and improves its ability to explore complex search spaces. The position update mechanism for this phase is defined in Equations (8)–(10).

$$RB = randn(1, Dim) \quad (8)$$

$$\frac{1}{3}T < t < \frac{2}{3}T, x_{i,j}^{new,P1} = x_{best} + \exp\left(\left(\frac{t}{T}\right)^4\right) \times (RB - 0.5) \times (x_{best} - x_{i,j}) \quad (9)$$

$$X_i = \begin{cases} X_i^{new,P1}, & \text{if } F_i^{new,P1} < F_i \\ X_i, & \text{otherwise} \end{cases} \quad (10)$$

where, $randn(1,D)$ generates a $1 \times Dim$ vector of random values drawn from a normal distribution. The term x_{best} represents the current best solution.

Attacking the Prey (Phase 3): Once the prey is sufficiently weakened, the secretary bird performs a decisive attack. In SBOA, this behavior is modeled by introducing a nonlinear perturbation factor. This factor enhances the adaptability of the algorithm and allows it to fine-tune candidate solutions as the search progresses. Additionally, a weighted Lévy flight mechanism is incorporated to further improve search accuracy and provide a balance between exploration and exploitation. The mathematical formulation of this phase is given in Equations (11)–(13).

$$t > \frac{2}{3}T, x_{i,j}^{newP1} = x_{best} + \left(\left(1 - \frac{t}{T}\right)^2 \times \frac{t}{T} \right) \times x_{i,j} \times RL \quad (11)$$

$$X_i = \begin{cases} X_i^{new,P1}, & \text{if } F_i^{new,P1} < F_i \\ X_i, & \text{otherwise} \end{cases} \quad (12)$$

To enhance the algorithm's accuracy, a weighted Lévy flight mechanism, referred to as RL, is incorporated.

$$RL = 0.5 \times Levy(Dim) \quad (13)$$

where, $Levy(Dim)$ corresponds to the Lévy flight distribution function and is calculated as described in Equation (14).

$$Levy(D) = s \times \frac{(u \times \sigma)}{|v|^{\frac{1}{\eta}}} \quad (14)$$

where, s and η are constants with values of 0.01 and 1.5, respectively. The variables u and v are random values within the interval $[0,1]$. The parameter σ is formulated as given in Equation (15).

$$\sigma = \left(\frac{\Gamma(1 + \eta) \times \sin\left(\frac{\pi\eta}{2}\right)}{\Gamma\left(\frac{1 + \eta}{2}\right) \times \eta \times 2^{\left(\frac{\eta - 1}{2}\right)}} \right)^{\frac{1}{\eta}} \quad (15)$$

where, Γ denotes the gamma function, while η takes the value of 1.5.

Escape-Based Exploitation Mechanism

In addition to hunting, secretary birds employ strategies to escape from predators. These behaviors are incorporated into SBOA to enhance exploitation capability. Two main escape strategies are considered:

- C_1 : Camouflage within the environment
- C_2 : Escaping through rapid movement (running or flying)

In the first case, the individual attempts to move toward a safer region by adjusting its position relative to the best solution. If this is not effective, the second strategy is applied, where the individual performs a more dynamic movement to escape. To maintain a balance between exploration and exploitation, a dynamic control parameter is introduced. This parameter adapts throughout the iterations, allowing the algorithm to emphasize exploration in early stages and exploitation in later stages. The mathematical representation of these strategies is given in Equations (16) and (17).

$$x_{i,j}^{new,P2} = \begin{cases} C_1: x_{best} + (2 \times RB - 1) \times \left(1 - \frac{t}{T}\right)^2 \times x_{i,j}, & \text{if } rand < r_i \\ C_2: x_{i,j} + R_2 \times (x_{random} - K \times x_{i,j}), & \text{otherwise} \end{cases} \quad (16)$$

$$X_i = \begin{cases} X_i^{new,P2}, & \text{if } F_i^{new,P2} < F_i \\ X_i, & \text{otherwise} \end{cases} \quad (17)$$

where, $r = 0.5$, and R_2 generates a $1 \times Dim$ vector of random values drawn from a normal distribution. The term x_{random} denotes a candidate solution randomly selected from the current iteration. The parameter K , which is an integer value computed according to Equation (18), determines the random selection of the strategies.

$$K = round(1 + rand(1,1)) \quad (18)$$

where, $rand(1,1)$ denotes the generation of a random number within the interval (0,1).

Binary Secretary Bird Optimization Algorithm (BSBOA)

SBOA was initially developed for continuous optimization tasks. Nevertheless, many real-world applications involve discrete or binary search spaces. A method developed for continuous domains cannot be directly applied to discrete spaces without modification. To address discrete problems, the decision variables of the method must be adapted to store and process data in a discrete form.

The binary search space is a specific type of discrete search space in which decision variables can take only two possible values, namely “0” and “1”. A wide range of methods has been introduced in the literature to convert continuous search spaces into binary domains, with transfer functions being among the most widely used and established approaches. These functions map continuous values into the interval [0,1]. The resulting values are then compared with a predefined threshold and converted into binary values, either 0 or 1.

In the literature, various methods have been proposed to transform continuous search spaces into binary ones, including S, U, V, Z, and taper-shaped transfer functions, as well as mod-based, XOR-based, and angle modulation techniques. Each of these methods has its own advantages and disadvantages.

In this study, the widely used S-shaped transfer function is employed for this transformation. The S-shaped transfer function is given in Equation (19).

$$T(a) = \frac{1}{1 + e^{-x}} \quad (19)$$

where, x represents the decision variables in SBOA; in other words, it denotes the values in the position vector of each individual. The position vector of each individual, consisting of real-valued elements, is provided as input to the corresponding transfer function. Equation (19) produces an output for each decision variable in the solution vector, yielding real values within the interval [0,1]. These values are then converted into binary values (0 or 1) using Equation (20).

$$X_{i,j}^{bin} = \begin{cases} 0, & \text{if } rand < T(a) \\ 1, & \text{if } rand \geq T(a) \end{cases} \quad (20)$$

where, $T(a)$ represents the value returned by the transfer function. This function is applied to each position of every individual, and the resulting values are converted into binary form according to Equation (20).

In this study, the original structure of SBOA is preserved, and only a transfer function is applied after determining the new position vectors of individuals to convert them into the binary search space. No additional modifications are introduced. In this way, the performance of the original SBOA is analyzed on the knapsack problem, which is one of the binary optimization problems.

Results and Discussion

This study focuses on the one-dimensional binary knapsack problem. The format of the dataset used in the problem is presented in Figure 2. The first row of the dataset contains the number of items and the capacity of the knapsack, respectively. Each subsequent row corresponds to an item, where the first and second columns represent the profit and weight of the item, respectively.

In the solution vector, an item is represented by 1 if it is included in the knapsack and by 0 otherwise. Accordingly, the size of the solution vector of individuals varies depending on the problem dimension. In the experimental studies, a total of 28 datasets were used, consisting of 10 small-scale and 18 large-scale instances from (Pisinger, 2005). The details of the datasets are presented in Table 1.

Table 1. Characteristics of the knapsack problem instances used

Instance	Type	Dimension	Optimum Value
Ins1	small-scale	10	295
Ins2		20	1024
Ins3		4	35
Ins4		4	23
Ins5		15	481.0694
Ins6		10	52
Ins7		7	107
Ins8		23	9767
Ins9		5	130
Ins10		20	1025
Ins11	large-scale	100	9147
Ins12		200	11238
Ins13		500	28857
Ins14		1000	54503
Ins15		2000	110625
Ins16		5000	276457
Ins17		100	1514
Ins18		200	1634
Ins19		500	4566
Ins20		1000	9052
Ins21		2000	18051
Ins22		5000	44356
Ins23		100	2397
Ins24		200	2697
Ins25		500	7117
Ins26		1000	14390
Ins27		2000	28919
Ins28		5000	72505

All problem instances are one-dimensional. In addition, each item can be used only once. The best, average, worst, and standard deviation values were calculated of obtained results. Furthermore, the GAP of each result was computed according to Equation (21). In this equation, the average value represents the average of the best results obtained from 30 independent runs. All results are presented in Table 2.

$$GAP = \frac{opt - avg}{opt} \times 100 \quad (21)$$

where, *opt* denotes the optimal value for the corresponding problem (i.e., the known best solution), while *avg* represents the average of the best values obtained from 30 independent runs for that problem.

94 485
506 326
416 248
992 421
649 322
237 795
457 43
815 845
446 955
422 252
791 9
359 901
667 122
598 94

Figure 2. Dataset format

Table 2. Results obtained from BSBOA

Instance	Optimum	Best	Avg.	Worst	Std.	GAP
Ins1	295	295	295	295	0	0
Ins2	1024	1024	1004,70	978	15,96	1,88
Ins3	35	35	35	35	0	0
Ins4	23	22	22	22	0	0
Ins5	481.0694	481.0694	481.0694	481.0694	0	0
Ins6	52	52	52	52	0	0
Ins7	107	107	107	107	0	0
Ins8	9767	9767	9767	9767	0	0
Ins9	130	130	130	130	0	0
Ins10	1025	1025	1002,1	973	18,36	2,23
Ins11	9147	9147	9093,8	8929	87,25	0,58
Ins12	11238	11227	11142,5	11007	100,13	0,85
Ins13	28857	26670	26087,5	25496	324,14	9,60
Ins14	54503	47503	46672,90	46211	374,48	14,37
Ins15	110625	91776	91124,10	90259	572,97	17,63
Ins16	276457	216893	215401,00	213872	914,99	22,09
Ins17	1514	1512	1512	1512	0	0,13
Ins18	1634	1634	1634,00	1634	0	0
Ins19	4566	4453	4432,60	4404	14,56	2,92
Ins20	9052	8595	8545,40	8480	36,45	5,60
Ins21	18051	16877	16744,80	16623	79,78	7,24
Ins22	44356	40620	40465,90	40328	85,29	8,77
Ins23	2397	2397	2392,60	2390	3,37	0,18
Ins24	2697	2697	2694,60	2691	2,32	0,09
Ins25	7117	6707	6620,40	6595	31,10	6,98
Ins26	14390	13077	12985,20	12904	43,73	9,76
Ins27	28919	25512	25295,40	25178	108,61	12,53
Ins28	72505	62543	61723,70	61397	324,96	14,87

As shown in Table 2, successful results have been obtained in small-scale problems using BSBOA. Specifically, it is observed that the optimum value is reached in all 30 independent tests for all eight low-dimensional problems except Ins2 and Ins10. As expected, the quality of the results decreases as the problem size increases, which is also reflected in the GAP ratios. However, two exceptions were observed in problems Ins18 and Ins24. Apart from these instances, it is observed that in all datasets, the deviation from the optimum solution increases proportionally with the problem size.

In addition, the iteration value of the method has been kept independent of the problem size. The iteration value is given as the same for every problem. Therefore, the computation times of the method have changed proportionally with the problem size. For 4-dimensional problems, this time is approximately 9 seconds in a

system with the hardware specifications mentioned earlier, while for a 5000-dimensional problem with the largest dimensions, this time is approximately 3.5 hours.

Conclusion

In this study, the performance of the recently introduced Secretary Bird Optimization Algorithm (SBOA) is investigated on binary optimization problems. Since SBOA is originally designed for continuous search spaces, it cannot be directly applied to binary problems. Therefore, the algorithm is adapted to the binary search space using an S-shaped transfer function.

Subsequently, the adapted version, referred to as BSBOA, is applied to the well-known binary knapsack problem. The dataset consists of a total of 28 problem instances, including 10 small-scale and 18 large-scale cases. The results show that BSBOA achieves optimal solutions for all small-scale problems. However, for large-scale problems, the solutions tend to deviate from the optimal values. In addition, the computational time of the method increases with the problem size. Overall, the findings indicate that BSBOA, in its current form, is capable of producing high-quality results for knapsack problems with dimensions up to 100.

Recommendations

The experimental results indicate that improvements are needed for large-scale problems in terms of both solution quality and computational time. To enhance solution quality, alternative transfer functions can be explored, or hybrid approaches can be developed. Additionally, to reduce computational time, improvements may be made to the repair mechanism used for handling infeasible solutions or to the initialization of the population.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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Author(s) Information

Vahit Tongur

Konya Technical University
Ardıçlı Mahallesi Rauf Orbay Cd. 42250 Selçuklu/Konya,
Türkiye
ORCID iD: <https://orcid.org/0000-0001-5419-7839>
*Contact e-mail: vtongur@ktun.edu.tr

Aysen Kucukyaghioglu

Konya Technical University
Ardıçlı Mahallesi Rauf Orbay Cd. 42250 Selçuklu/Konya,
Türkiye
ORCID iD: <https://orcid.org/0009-0006-2986-5034>

*Corresponding author(s) contact email

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A Binary Hiking Optimization Algorithm for 0/1 Knapsack Problem

Aybuke Babadag

Konya Technical University

Abstract: The 0/1 knapsack problem is one of the prominent NP-hard binary optimization problems. Solving such problems using exact methods can be computationally expensive. Therefore, metaheuristic methods which offer optimal or near optimal solutions in a reasonable time, are commonly utilized for such tasks. The Hiking Optimization Algorithm (HOA) is a recently proposed metaheuristic optimization algorithm that is inspired by the similarity between the hikers' navigation of steep terrain and the search process within the optimization problem's search space. However, the basic algorithm is initially proposed for continuous optimization problems. To apply the algorithm to binary optimization tasks, certain adaptations are required. One of the commonly used binarization techniques involves using a transfer function to convert continuous decision variables into binary counterparts. In this study, HOA is binarized using four different variants for each of the following transfer function types: S-shaped, U-shaped, Z-shaped, and T-shaped. Furthermore, a repair function is adopted to tackle the infeasible solutions produced by the algorithm. The performance of the proposed binary HOA (binHOA) algorithm is assessed on two standard benchmark datasets. The results are compared with the binary versions of the well-known optimization algorithms. The experimental results indicate that the proposed binary version of HOA is a competitive alternative for the 0/1 knapsack problem.

Keywords: Hiking optimization algorithm, 0/1 knapsack problem, Transfer functions

Introduction

The knapsack problem is a well-known combinatorial optimization problem that aims to find the combination of items that maximizes total profit while ensuring that the sum of their weights does not exceed the knapsack's capacity (Zhou et al., 2023). The knapsack problem has a variety of real-world applications, including resource allocation (Reniers & Sörensen, 2013), container loading (Pisinger, 2002), and real estate property maintenance (Taillandier et al., 2017). This problem has several variants, such as the multiple-choice knapsack, multi-dimensional knapsack, fractional knapsack, and 0/1 knapsack, that cover numerous application areas (Mahafzah et al., 2025). This study focuses on the 0/1 knapsack problem. In the 0/1 knapsack problem, if an item is selected, the value of the decision variable associated with it becomes 1; otherwise, it becomes 0, indicating that the item is not selected. The knapsack problem belongs to the NP-hard class. Therefore, finding a solution in a reasonable time using exact methods may require excessive computation time for some problem instances, especially high dimensional ones (Pisinger, 2005). Metaheuristic algorithms can be used as an alternative due to their stochastic nature, which makes it relatively efficient to find optimal or near-optimal solutions in a reasonable time.

In recent years, numerous metaheuristic algorithms have been proposed to address the 0/1 knapsack problem. In the study by Abdel-Basset et al. (2021), the marine predators algorithm (MPA) was applied to the 0/1 knapsack problem, and the basic algorithm was binarized using S-shaped and V-shaped transfer functions. Similarly, in the study by Sun et al. (2021), the binary particle swarm optimization (PSO) algorithm was used to solve the 0/1 knapsack problem. Four different variants of Z-shaped transfer functions were employed to convert continuous decision variables into binary ones. To ensure that the generated solutions complied with the constraints, a penalty function was utilized. Shu et al. (2022) proposed a hybrid model combining the binary ant colony

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optimization (ACO) algorithm and a modified version of the hybrid rice optimization (HRO) algorithm to solve the large-scale 0/1 knapsack problem. In addition, a two-phase repair strategy was used to handle infeasible solutions. In the study by Yildizdan and Baş (2023), the artificial jellyfish search (AJS) algorithm was binarized to solve the 0/1 knapsack problem, where the continuous search space was mapped to a binary version using S-shaped and V-shaped transfer functions. Büyüköz and Haklı (2023) proposed a binary version of the honey badger algorithm (HBA) for solving the 0/1 knapsack problem. In the binarization process, V-shaped, S-shaped, U-shaped, T-shaped, Tangent Sigmoid, O-shaped, and Z-shaped transfer functions were used. Similarly, Ervural and Haklı (2023) proposed a binary version of the reptile search algorithm (RSA) for the 0/1 knapsack problem. Various transfer functions, including V-shaped, S-shaped, U-shaped, T-shaped, and Z-shaped, were utilized in the binarization process. In addition, a stochastic repair and improvement method was introduced to handle infeasible solutions generated by the algorithm. Limane et al. (2024) introduced a binary version of the electric eel foraging optimization (EEFO) algorithm for solving the 0/1 knapsack problem. S-shaped and V-shaped transfer functions were employed to transfer the continuous search space into binary search space. To further improve the performance of the proposed algorithm, an enhanced repair and improvement (RI) method was introduced to tackle infeasible solutions. Erdoğan et al. (2025) proposed a binary version of the grey wolf optimizer (GWO), namely the binary dynamic grey wolf optimizer (BDGWO), to solve binary optimization problems. The effectiveness of the BDGWO algorithm was assessed using the 0/1 knapsack problem. Ihsan and Sag (2025) introduced a binary version of the puma optimizer (PO) algorithm, which was binarized using S-shaped and V-shaped transfer functions. The performance of the proposed algorithm was evaluated on the 0/1 knapsack problem.

As seen from the studies in the literature, various metaheuristic optimization algorithms have been applied to the 0/1 knapsack problem. One of the recently proposed metaheuristic optimization algorithms is the hiking optimization algorithm (HOA), which is inspired by the resemblance between a hiker's traversal of the mountainous terrain and the exploration of an optimization problem's search space. However, it is observed from the literature that there is no notable binary variant of the HOA introduced to solve the knapsack problem. To address this gap, the recently introduced hiking optimization algorithm is binarized in this study to solve the 0/1 knapsack problem. It is also observed that transfer functions for converting the search space from continuous to binary are commonly used in the literature. In this study, four different types of transfer functions, namely S-shaped (Mirjalili & Lewis, 2013), U-shaped (Mirjalili et al., 2020), Z-shaped (Guo et al., 2020), and T-shaped (He et al., 2022), are used to binarize the HOA. The performance of the proposed binary version of the HOA, called binary HOA (binHOA), is evaluated on two well-known benchmark datasets. The performance of the binHOA is compared with six well-known metaheuristic algorithms.

Method

The 0/1 Knapsack Problem

In the knapsack problem it is assumed that there is a knapsack with a capacity of W and n items with weight of w and a profit of p . Let x_i be a vector holds the information whether the item i is included in the knapsack. The objective function of the knapsack problem is as follows (Sakib et al., 2025):

$$\text{maximize } \sum_{i=1}^N p_i x_i$$

Subject to constraints:

$$\sum_{i=1}^N w_i x_i \leq W$$

$$x_i \in \{0,1\}$$

where $x_i=1$ means i -th item is included and $x_i=0$ means i -th item is not included. The objective is to determine an x vector that maximizes the total profit and does not exceed the capacity of the knapsack.

Hiking Optimization Algorithm

HOA is a human-inspired metaheuristic algorithm based on the hiking activity (Oladejo et al., 2024). The algorithm is mathematically modeled using Tobler's hiking function, an exponential function that determines a hiker's walking speed, as a function of terrain slope. The Tobler's hiking function given as follows:

$$W_{i,t} = 6e^{-3.5|S_{i,t}+0.05|}$$

where $W_{i,t}$ represents the velocity of the i -th hiker at the t -th iteration. $S_{i,t}$ represents the slope of the terrain and calculated as follows:

$$S_{i,t} = \frac{dh}{dx} = \tan\theta_{i,t}$$

where dh represents the difference in elevation, dx represents the distance traversed by the hiker, and the θ denotes the inclination angle of the terrain, ranging from 0° to 50° . The current velocity of the i -th hiker is calculated as follows:

$$W_{i,t} = W_{i,t-1} + \gamma_{i,t}(\beta_{best} - \alpha_{i,t}\beta_{i,t})$$

$\gamma_{i,t}$ is a uniformly distributed number in the range $[0,1]$, $W_{i,t}$ and $W_{i,t-1}$ represents the current and initial velocity of the i -th hiker respectively. β_{best} is the position of the lead hiker and $\alpha_{i,t}$ is the sweep factor (SF) of the i -th hiker ranging from 1 to 3. SF prevents hikers from deviating excessively from the lead hiker, ensuring both navigational guidance and signal reception are maintained. The position of the i -th hiker is updated as follows:

$$\beta_{i,t+1} = \beta_{i,t} + W_{i,t}$$

The pseudocode of the HOA is given in Algorithm 1.

Algorithm 1 Pseudocode of the HOA

```

input:  $Ub$  (upper bound),  $Lb$  (lower bound),  $T$  (maximum iteration number),  $I$  (number of hikers),  $d$ 
(dimension)
1:  $F \leftarrow$  initialize fitness vector
2:  $F_{best} \leftarrow$  initialize best fitness vector
3:  $\beta \leftarrow$  initialize hikers' position randomly
4: for  $i \leftarrow 1$  to  $I$ 
5:    $F_i \leftarrow$  Calculate the fitness of the  $i$ -th hiker
6: end for
7:  $F_{best,1} \leftarrow$  initial best fitness of hikers
8: for  $t \leftarrow 1$  to  $T$ 
9:    $F_{best,t} \leftarrow$  best fitness value
10:   $\beta_{best} \leftarrow$  position of the best solution
11:  for  $i \leftarrow 1$  to  $I$ 
12:     $\beta_{i,t} \leftarrow$  initial position of the  $i$ -th hiker
13:     $\theta_{i,t} \leftarrow$  elevation angle
14:     $S_{i,t} \leftarrow$  calculate the slope
15:     $W_{i,t-1} \leftarrow$  calculate the initial velocity of the  $i$ -th hiker
16:     $W_{i,t} \leftarrow$  calculate the actual velocity of the  $i$ -th hiker
17:     $\beta_{i,t+1} \leftarrow$  update the position of the  $i$ -th hiker
18:    Apply boundary constraints to  $\beta_{i,t}$  within  $[Lb, Ub]$ 
19:    if  $F_n \leq F(n)$ 
20:       $\gamma(n,:) \leftarrow \beta_{i,t+1}$ 
21:       $F(n) \leftarrow F_n$ 
22:    end if
23:  end for
24:   $F_{sol}(i+1) \leftarrow \min(F)$ 
25: end for
26:  $F_{opt\_sol} \leftarrow \operatorname{argmin}(F_{sol})$ 
27: return  $F_{opt\_sol}$ 
    
```

Proposed Binary Hiking Optimization Algorithm

Hiking optimization algorithm is initially proposed for solving continuous optimization problems. It requires certain modifications to adapt the HOA to solve binary optimization problems such as the 0/1 knapsack. There are various techniques that transform real-valued decision variables into binary counterparts. Transfer functions are one of the common methods for this purpose. In this study, four different types of transfer functions are used. Four variants of each transfer function, each with different parameters, were evaluated and the best-performing one was determined. The formulations of the transfer functions are given in Table 1.

Table 1. The formulations of the transfer functions: S-shaped, U-shaped, Z-shaped, and T-shaped

S-shaped	U-shaped	Z-shaped	T-shaped
$s_1(x) = \frac{1}{1 + e^{-2x}}$	$u_1(x) = x^{1.5}$	$z_1(x) = \sqrt{1 - 2^x}$	$t_1(x) = \frac{\sqrt{x}}{\sqrt{A}}$
$s_2(x) = \frac{1}{1 + e^{-x}}$	$u_2(x) = x^2$	$z_2(x) = \sqrt{1 - 5^x}$	$t_2(x) = \frac{ x }{ A }$
$s_3(x) = \frac{1}{1 + e^{-x/2}}$	$u_3(x) = x^3$	$z_3(x) = \sqrt{1 - 8^x}$	$t_3(x) = \frac{\sqrt[3]{x}}{\sqrt[3]{A}}$
$s_4(x) = \frac{1}{1 + e^{-x/3}}$	$u_4(x) = x^4$	$z_4(x) = \sqrt{1 - 20^x}$	$t_4(x) = \frac{\sqrt[4]{x}}{\sqrt[4]{A}}$

After each position updates in the basic algorithm, the continuous position vector is converted to a binary vector as follows:

$$X_{bin} = \begin{cases} 1 & \text{if } TF(x) \leq T \\ 0 & \text{else} \end{cases}$$

Algorithm 2 Pseudocode of the binHOA

```

input:  $Ub$  (upper bound),  $Lb$  (lower bound),  $T$  (maximum iteration number),
 $I$  (number of hikers),  $d$  (dimension)
1:  $F \leftarrow$  initialize fitness vector
2:  $F_{best} \leftarrow$  initialize best fitness vector
3:  $\beta \leftarrow$  initialize continuous position vector randomly
4:  $\beta_{bin} \leftarrow$  initialize binary position vector randomly
5: for  $i \leftarrow 1$  to  $I$ 
6:    $F_i \leftarrow$  Calculate the fitness of the  $i$ -th hiker
7: end for
8:  $F_{best,1} \leftarrow$  initial best fitness of hikers
9: for  $t \leftarrow 1$  to  $T$ 
10:   $F_{best,t} \leftarrow$  best fitness value
11:   $\beta_{best} \leftarrow$  position of the best solution
12:  for  $i \leftarrow 1$  to  $I$ 
13:     $\beta_{i,t} \leftarrow$  initial position of the  $i$ -th hiker
14:     $\theta_{i,t} \leftarrow$  elevation angle
15:     $S_{i,t} \leftarrow$  calculate the slope
16:     $W_{i,t-1} \leftarrow$  calculate the initial velocity of the  $i$ -th hiker
17:     $W_{i,t} \leftarrow$  calculate the actual velocity of the  $i$ -th hiker
18:     $\beta_{i,t+1} \leftarrow$  update the position of the  $i$ -th hiker
19:    Apply boundary constraints to  $\beta_{i,t}$  within  $[Lb, Ub]$ 
20:     $\beta_{bin} \leftarrow$  binarize the continuous position vector
21:    Apply the repair function
22:    if  $F_n \leq F(n)$ 
23:       $\gamma(n,:) \leftarrow \beta_{i,t+1}$ 
24:       $F(n) \leftarrow F_n$ 
25:    end if
26:  end for
27:   $F_{sol}(i+1) \leftarrow \min(F)$ 
28: end for
29:  $F_{opt\_sol} \leftarrow \operatorname{argmin}(F_{sol})$ 
30: return  $F_{opt\_sol}$ 
    
```

where X_{bin} is a binary position vector for the corresponding continuous position vector x , T is a threshold value, and TF denotes the transfer function. Following Ervural and Hakli (2023), the threshold values are set to a random number in the range $[0, 1]$ for S-, U-, and Z-shaped functions, and to 0.5 for the T-shaped function. To further improve the performance of the proposed binHOA, a stochastic repair function (Ervural & Hakli, 2023) is adopted. Following the binarization of the continuous position vectors, the repair function is applied, thereby ensuring that all solutions in the population are feasible. The pseudocode of the binHOA is given in Algorithm2.

Results and Discussion

Datasets

This study employs two standard benchmark datasets. The small-scale dataset consists of 10 problem instances, with problem dimensions ranging from 4 to 20. The details of the small-scale dataset (Zou et al., 2011) are given in Table 2.

Table 2. The small-scale dataset

Problem	Dimension	Optimum Value
f1	10	295
f2	20	1024
f3	4	35
f4	4	23
f5	15	481.0694
f6	10	50
f7	7	107
f8	23	9767
f9	5	130
f10	20	1025

The other benchmark dataset is a medium-scale dataset (Bansal & Deep, 2012), which consists of 25 instances. The dimensions of the problems in the dataset range from 8 to 24. The details of the dataset are given in Table 3.

Table 3. The medium-scale dataset

Problem	Dimension	Optimum Value	Problem	Dimension	Optimum Value
ks_8a	8	3924400	ks_16d	16	9348889
ks_8b	8	3813669	ks_16e	16	7769117
ks_8c	8	3347452	ks_20a	20	10727049
ks_8d	8	4187707	ks_20b	20	9818261
ks_8e	8	4955555	ks_20c	20	10714023
ks_12a	12	5688887	ks_20d	20	8929156
ks_12b	12	6473019	ks_20e	20	9357969
ks_12c	12	5170626	ks_24a	24	13549094
ks_12d	12	6941564	ks_24b	24	12233713
ks_12e	12	5337472	ks_24c	24	12448780
ks_16a	16	7850983	ks_24d	24	11815315
ks_16b	16	9352998	ks_24e	24	13940099
ks_16c	16	9151147			

Experimental Results

The proposed binHOA is evaluated on two different scale benchmark datasets. The results are compared with the binary versions of six different well-known optimization algorithms namely, particle swarm optimization (PSO) (Kennedy & Eberhart, 1995), differential evolution (DE) (Storn & Price, 1997), artificial bee colony (ABC) (Karaboga, 2005; Karaboga & Basturk, 2007), grey wolf optimizer (GWO) (Mirjalili et al., 2014), whale optimization algorithm (WOA) (Mirjalili & Lewis, 2016), and sparrow search algorithm (SSA) (Xue & Shen, 2020). Due to the stochastic nature of the algorithms, each is independently run 20 times. The maximum number of iterations and the population size are set to 5000 and 20, respectively, as in (Abdel-Basset et al., 2021; Yildizdan & Baş, 2023). To ensure fairness in the experiments, the same parameter settings are applied to all algorithms, as summarized in Table 4.

Table 4. Parameter setting

Population size	20
Maximum number of iterations	5000
Number of runs	20

The performances of the algorithms are evaluated in terms of standard deviation, gap values, mean fitness value, best fitness value, and worst fitness value. The percentage difference between the actual optimum value and the optimum value generated by the algorithm is measured using the Gap metric, which is calculated as follows:

$$Gap = \begin{cases} \frac{opt - m}{opt} \times 100, & \text{for maximization} \\ \frac{m - opt}{opt} \times 100, & \text{for minimization} \end{cases}$$

where m is the mean fitness value across all runs and opt is the optimal value of the problem instance. The experimental results of the binHOA on small-scale dataset are presented in Tables 5 and 6.

Table 5. The experimental results of the binHOA on small-scale dataset (s1-u4)

TF	metric	f1	f2	f3	f4	f5	f6	f7	f8	f9	f10
s1	mean	295	1024	35	23	481.0694	52	107	9766.6	130	1025
	min	295	1024	35	23	481.0694	52	107	9765	130	1025
	max	295	1024	35	23	481.0694	52	107	9767	130	1025
	std	0	0	0	0	0	0	0	0.8208	0	0
	gap	0	0	0	0	0	0	0	0.0041	0	0
s2	mean	295	1024	35	23	481.0694	52	107	9767	130	1025
	min	295	1024	35	23	481.0694	52	107	9767	130	1025
	max	295	1024	35	23	481.0694	52	107	9767	130	1025
	std	0	0	0	0	0	0	0	0	0	0
	gap	0	0	0	0	0	0	0	0	0	0
s3	mean	295	1024	35	23	481.0694	52	107	9767	130	1025
	min	295	1024	35	23	481.0694	52	107	9767	130	1025
	max	295	1024	35	23	481.0694	52	107	9767	130	1025
	std	0	0	0	0	0	0	0	0	0	0
	gap	0	0	0	0	0	0	0	0	0	0
s4	mean	295	1024	35	23	481.0694	52	107	9767	130	1025
	min	295	1024	35	23	481.0694	52	107	9767	130	1025
	max	295	1024	35	23	481.0694	52	107	9767	130	1025
	std	0	0	0	0	0	0	0	0	0	0
	gap	0	0	0	0	0	0	0	0	0	0
u1	mean	295	1024	35	23	481.0694	52	107	9767	130	1025
	min	295	1024	35	23	481.0694	52	107	9767	130	1025
	max	295	1024	35	23	481.0694	52	107	9767	130	1025
	std	0	0	0	0	0	0	0	0	0	0
	gap	0	0	0	0	0	0	0	0	0	0
u2	mean	295	1024	35	23	481.0694	52	107	9767	130	1025
	min	295	1024	35	23	481.0694	52	107	9767	130	1025
	max	295	1024	35	23	481.0694	52	107	9767	130	1025
	std	0	0	0	0	0	0	0	0	0	0
	gap	0	0	0	0	0	0	0	0	0	0
u3	mean	295	1024	35	23	481.0694	52	107	9767	130	1025
	min	295	1024	35	23	481.0694	52	107	9767	130	1025
	max	295	1024	35	23	481.0694	52	107	9767	130	1025
	std	0	0	0	0	0	0	0	0	0	0
	gap	0	0	0	0	0	0	0	0	0	0
u4	mean	295	1024	35	23	481.0694	52	107	9767	130	1025
	min	295	1024	35	23	481.0694	52	107	9767	130	1025
	max	295	1024	35	23	481.0694	52	107	9767	130	1025
	std	0	0	0	0	0	0	0	0	0	0
	gap	0	0	0	0	0	0	0	0	0	0

Table 6. The experimental results of the binHOA on small-scale dataset (z1-t4)

TF	metric	f1	f2	f3	f4	f5	f6	f7	f8	f9	f10
z1	mean	295	1024	35	23	481.0694	52	107	9767	130	1025
	min	295	1024	35	23	481.0694	52	107	9767	130	1025
	max	295	1024	35	23	481.0694	52	107	9767	130	1025
	std	0	0	0	0	0	0	0	0	0	0
	gap	0	0	0	0	0	0	0	0	0	0
z2	mean	295	1024	35	23	481.0694	52	107	9767	130	1025
	min	295	1024	35	23	481.0694	52	107	9767	130	1025
	max	295	1024	35	23	481.0694	52	107	9767	130	1025
	std	0	0	0	0	0	0	0	0	0	0
	gap	0	0	0	0	0	0	0	0	0	0
z3	mean	295	1024	35	23	481.0694	52	107	9767	130	1025
	min	295	1024	35	23	481.0694	52	107	9767	130	1025
	max	295	1024	35	23	481.0694	52	107	9767	130	1025
	std	0	0	0	0	0	0	0	0	0	0
	gap	0	0	0	0	0	0	0	0	0	0
z4	mean	295	1024	35	23	481.0694	52	107	9767	130	1025
	min	295	1024	35	23	481.0694	52	107	9767	130	1025
	max	295	1024	35	23	481.0694	52	107	9767	130	1025
	std	0	0	0	0	0	0	0	0	0	0
	gap	0	0	0	0	0	0	0	0	0	0
t1	mean	295	1024	35	23	481.0694	52	107	9767	130	1025
	min	295	1024	35	23	481.0694	52	107	9767	130	1025
	max	295	1024	35	23	481.0694	52	107	9767	130	1025
	std	0	0	0	0	0	0	0	0	0	0
	gap	0	0	0	0	0	0	0	0	0	0
t2	mean	295	1024	35	23	481.0694	52	107	9767	130	1025
	min	295	1024	35	23	481.0694	52	107	9767	130	1025
	max	295	1024	35	23	481.0694	52	107	9767	130	1025
	std	0	0	0	0	0	0	0	0	0	0
	gap	0	0	0	0	0	0	0	0	0	0
t3	mean	295	1024	35	23	481.0694	52	107	9766.8	130	1025
	min	295	1024	35	23	481.0694	52	107	9765	130	1025
	max	295	1024	35	23	481.0694	52	107	9767	130	1025
	std	0	0	0	0	0	0	0	0.6156	0	0
	gap	0	0	0	0	0	0	0	0.002	0	0
t4	mean	295	1024	35	23	481.0694	52	107	9767	130	1025
	min	295	1024	35	23	481.0694	52	107	9767	130	1025
	max	295	1024	35	23	481.0694	52	107	9767	130	1025
	std	0	0	0	0	0	0	0	0	0	0
	gap	0	0	0	0	0	0	0	0	0	0

As seen in Tables 5 and 6, the optimum values are achieved in all runs with all transfer functions for all problems, except for problem f8 with transfer functions s1 and t3. Therefore, the gap and standard deviation values are 0 for the problems for which the optimum values were achieved in all runs. The experimental results of the binHOA on medium-scale dataset are presented in Tables 7 and 8.

Table 7. The experimental results of the binHOA on medium-scale dataset (s1-u4)

TF	metric	ks 8a	ks 8b	ks 8c	ks 8d	ks 8e	ks 12a	ks 12b	ks 12c	ks 12d	ks 12e	ks 16a	ks 16b	ks 16c
s1	mean	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7838659	9352998	9151147
	min	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7832023	9352998	9151147
	max	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7850983	9352998	9151147
	std	0	0	0	0	0	0	0	0	0	0	9278.275	0	0
	gap	0	0	0	0	0	0	0	0	0	0	0.157	0	0
s2	mean	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7837711	9352998	9151147
	min	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7832023	9352998	9151147
	max	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7850983	9352998	9151147
	std	0	0	0	0	0	0	0	0	0	0	8914.278	0	0
	gap	0	0	0	0	0	0	0	0	0	0	0.1691	0	0

s3	mean	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7837711	9352998	9151147
	min	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7832023	9352998	9151147
	max	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7850983	9352998	9151147
	std	0	0	0	0	0	0	0	0	0	0	8914.278	0	0
	gap	0	0	0	0	0	0	0	0	0	0	0.1691	0	0
s4	mean	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7834867	9352998	9151147
	min	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7832023	9352998	9151147
	max	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7850983	9352998	9151147
	std	0	0	0	0	0	0	0	0	0	0	6945.95	0	0
	gap	0	0	0	0	0	0	0	0	0	0	0.2053	0	0
u1	mean	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7837711	9352998	9151147
	min	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7832023	9352998	9151147
	max	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7850983	9352998	9151147
	std	0	0	0	0	0	0	0	0	0	0	8914.278	0	0
	gap	0	0	0	0	0	0	0	0	0	0	0.1691	0	0
u2	mean	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7838659	9352998	9151147
	min	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7832023	9352998	9151147
	max	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7850983	9352998	9151147
	std	0	0	0	0	0	0	0	0	0	0	9278.275	0	0
	gap	0	0	0	0	0	0	0	0	0	0	0.157	0	0
u3	mean	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7837711	9352998	9151147
	min	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7832023	9352998	9151147
	max	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7850983	9352998	9151147
	std	0	0	0	0	0	0	0	0	0	0	8914.278	0	0
	gap	0	0	0	0	0	0	0	0	0	0	0.1691	0	0
u4	mean	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7837711	9352998	9151147
	min	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7832023	9352998	9151147
	max	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7850983	9352998	9151147
	std	0	0	0	0	0	0	0	0	0	0	8914.278	0	0
	gap	0	0	0	0	0	0	0	0	0	0	0.1691	0	0
z1	mean	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7839607	9352998	9151147
	min	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7832023	9352998	9151147
	max	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7850983	9352998	9151147
	std	0	0	0	0	0	0	0	0	0	0	9529.764	0	0
	gap	0	0	0	0	0	0	0	0	0	0	0.1449	0	0
z2	mean	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7841503	9352998	9151147
	min	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7832023	9352998	9151147
	max	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7850983	9352998	9151147
	std	0	0	0	0	0	0	0	0	0	0	9726.275	0	0
	gap	0	0	0	0	0	0	0	0	0	0	0.1207	0	0
z3	mean	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7840555	9352998	9151147
	min	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7832023	9352998	9151147
	max	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7850983	9352998	9151147
	std	0	0	0	0	0	0	0	0	0	0	9677.521	0	0
	gap	0	0	0	0	0	0	0	0	0	0	0.1328	0	0
z4	mean	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7844347	9352998	9151147
	min	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7832023	9352998	9151147
	max	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7850983	9352998	9151147
	std	0	0	0	0	0	0	0	0	0	0	9278.275	0	0
	gap	0	0	0	0	0	0	0	0	0	0	0.0845	0	0
t1	mean	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7838659	9352998	9151147
	min	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7832023	9352998	9151147
	max	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7850983	9352998	9151147
	std	0	0	0	0	0	0	0	0	0	0	9278.275	0	0
	gap	0	0	0	0	0	0	0	0	0	0	0.157	0	0
t2	mean	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7840555	9352998	9151147
	min	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7832023	9352998	9151147
	max	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7850983	9352998	9151147
	std	0	0	0	0	0	0	0	0	0	0	9677.521	0	0
	gap	0	0	0	0	0	0	0	0	0	0	0.1328	0	0
t3	mean	3924400	3813669	3347452	4187707	4955555	5688563	6498597	5170626	6992404	5337472	7836763	9352998	9151147
	min	3924400	3813669	3347452	4187707	4955555	5682404	6498597	5170626	6992404	5337472	7832023	9352998	9151147
	max	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7850983	9352998	9151147
	std	0	0	0	0	0	1449.643	0	0	0	0	8423.201	0	0
	gap	0	0	0	0	0	0.0057	0	0	0	0	0.1811	0	0
t4	mean	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7838659	9352998	9151147
	min	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7832023	9352998	9151147
	max	3924400	3813669	3347452	4187707	4955555	5688887	6498597	5170626	6992404	5337472	7850983	9352998	9151147
	std	0	0	0	0	0	0	0	0	0	0	9278.275	0	0
	gap	0	0	0	0	0	0	0	0	0	0	0.157	0	0

Table 8. The experimental results of the binHOA on medium-scale dataset (z1-t4)

TF	metric	ks 16d	ks 16e	ks 20a	ks 20b	ks 20c	ks 20d	ks 20e	ks 24a	ks 24b	ks 24c	ks 24d	ks 24e
s1	mean	9339131	7763733	10718043	9802868	10712717	8919683	9357969	13549094	12207002	12448780	11810051	13935497
	min	9336691	7750491	10717569	9774200	10712572	8893733	9357969	13549094	12196303	12448780	11810051	13929872
	max	9348889	7769117	10727049	9818261	10714023	8929156	9357969	13549094	12210480	12448780	11810051	13940099
	std	5005.954	7570.012	2119.792	21523.03	446.6084	15509.06	0	0	6181.478	0	0	5220.043
	gap	0.1044	0.0693	0.084	0.1568	0.0122	0.1061	0	0	0.2183	0	0	0.033
s2	mean	9339741	7758802	10718043	9811242	10712717	8923843	9357969	13549094	12212803	12448780	11810051	13936589
	min	9336691	7748170	10717569	9765998	10712572	8893733	9357969	13549094	12210480	12448780	11810051	13929872
	max	9348889	7769117	10727049	9818261	10714023	8929156	9357969	13549094	12233713	12448780	11810051	13940099
	std	5419.104	8931.956	2119.792	17211.94	446.6084	12977.13	0	0	7150.967	0	0	4911.345
	gap	0.0979	0.1328	0.084	0.0715	0.0122	0.0595	0	0	0.1709	0	0	0.0252
s3	mean	9340350	7762744	10717569	9813855	10712790	8923155	9357969	13549094	12211642	12448780	11810051	13936043
	min	9336691	7748170	10717569	9774200	10712572	8893733	9357969	13549094	12210480	12448780	11810051	13929872
	max	9348889	7769117	10717569	9818261	10714023	8929156	9357969	13549094	12233713	12448780	11810051	13940099
	std	5735.04	9022.258	0	13561.69	531.5703	13045.18	0	0	5195.057	0	0	5094.016
	gap	0.0913	0.082	0	0.0449	0.0115	0.0672	0	0	0.1804	0	0	0.0291

s4	mean	9340350	7760839	10717569	9813855	10712717	8923155	9357969	13549094	12213965	12448780	11810051	13938669
	min	9336691	7748170	10717569	9774200	10712572	8893733	9357969	13549094	12210480	12448780	11810051	13930566
	max	9348889	7769117	10717569	9818261	10714023	8929156	9357969	13549094	12233713	12448780	11810051	13940099
	std	5735.04	9567.416	0	13561.69	446.6084	13045.18	0	0	8511.353	0	0	3492.391
	gap	0.0913	0.1066	0	0.0449	0.0122	0.0672	0	0	0.1614	0	0	0.0103
u1	mean	9339741	7765960	10718043	9813855	10712645	8925614	9357969	13549094	12214440	12448780	11810051	13938600
	min	9336691	7750491	10717569	9774200	10712572	8893733	9357969	13549094	12196745	12448780	11810051	13929872
	max	9348889	7769117	10727049	9818261	10714023	8929156	9357969	13549094	12233713	12448780	11810051	13940099
	std	5419.104	6522.447	2119.792	13561.69	324.4535	10902.97	0	0	10346.96	0	0	3664.195
	gap	0.0979	0.0406	0.084	0.0449	0.0129	0.0397	0	0	0.1575	0	0	0.0108
u2	mean	9340960	7766149	10718991	9813855	10712862	8927780	9357969	13549094	12215127	12448780	11810051	13938669
	min	9336691	7754276	10717569	9774200	10712572	8915396	9357969	13549094	12210480	12448780	11810051	13930566
	max	9348889	7769117	10727049	9818261	10714023	8929156	9357969	13549094	12233713	12448780	11810051	13940099
	std	5969.219	6090.618	3472.975	13561.69	595.4778	4235.239	0	0	9534.622	0	0	3492.391
	gap	0.0848	0.0382	0.0751	0.0449	0.0108	0.0154	0	0	0.1519	0	0	0.0103
u3	mean	9341570	7760897	10717569	9811652	10712790	8926768	9357969	13549094	12214126	12448780	11810051	13937681
	min	9336691	7748170	10717569	9774200	10712572	8895152	9357969	13549094	12210480	12448780	11810051	13929872
	max	9348889	7769117	10717569	9818261	10714023	8929156	9357969	13549094	12233713	12448780	11810051	13940099
	std	6131.016	8629.159	0	16141.64	531.5703	8050.955	0	0	8472.317	0	0	4299.169
	gap	0.0783	0.1058	0	0.0673	0.0115	0.0267	0	0	0.1601	0	0	0.0173
u4	mean	9339131	7762381	10717569	9811242	10713080	8927385	9357969	13549094	12216288	12448780	11810051	13937135
	min	9336691	7748170	10717569	9765998	10712572	8893733	9357969	13549094	12210480	12448780	11810051	13929872
	max	9348889	7769117	10717569	9818261	10714023	8929156	9357969	13549094	12233713	12448780	11810051	13940099
	std	5005.954	8639.617	0	17211.94	710.0621	7920.824	0	0	10321.53	0	0	4649.295
	gap	0.1044	0.0867	0	0.0715	0.0088	0.0198	0	0	0.1424	0	0	0.0213
z1	mean	9341570	7765844	10717569	9818261	10712790	8926697	9357969	13549094	12215127	12448780	11810051	13939588
	min	9336691	7748170	10717569	9818261	10712572	8893733	9357969	13549094	12210480	12448780	11810051	13929872
	max	9348889	7769117	10717569	9818261	10714023	8929156	9357969	13549094	12233713	12448780	11810051	13940099
	std	6131.016	6825.751	0	0	531.5703	8345.116	0	0	9534.622	0	0	2286.827
	gap	0.0783	0.0421	0	0	0.0115	0.0275	0	0	0.1519	0	0	0.0037
z2	mean	9342790	7765218	10717569	9818261	10712862	8929156	9357969	13549094	12216288	12448780	11810051	13939588
	min	9336691	7750491	10717569	9818261	10712572	8929156	9357969	13549094	12210480	12448780	11810051	13929872
	max	9348889	7769117	10717569	9818261	10714023	8929156	9357969	13549094	12233713	12448780	11810051	13940099
	std	6257.442	6972.982	0	0	595.4778	0	0	0	10321.53	0	0	2286.827
	gap	0.0652	0.0502	0	0	0.0108	0	0	0	0.1424	0	0	0.0037
z3	mean	9344620	7767022	10717569	9818261	10712572	8929156	9357969	13549094	12217450	12448780	11810051	13940099
	min	9336691	7748170	10717569	9818261	10712572	8929156	9357969	13549094	12210480	12448780	11810051	13940099
	max	9348889	7769117	10717569	9818261	10712572	8929156	9357969	13549094	12233713	12448780	11810051	13940099
	std	5969.219	6447.351	0	0	0	0	0	0	10923.28	0	0	0
	gap	0.0457	0.0270	0	0	0	0	0	0	0.1329	0	0	0
z4	mean	9342790	7765538	10718517	9818261	10713007	8927385	9357969	13549094	12219773	12448780	11810051	13938669
	min	9336691	7748170	10717569	9818261	10712572	8893733	9357969	13549094	12210480	12448780	11810051	13930566
	max	9348889	7769117	10727049	9818261	10714023	8929156	9357969	13549094	12233713	12448780	11810051	13940099
	std	6257.442	7475.954	2917.882	0	682.2056	7920.824	0	0	11677.48	0	0	3492.391
	gap	0.0652	0.0461	0.0795	0	0.0095	0.0198	0	0	0.1139	0	0	0.0103
f1	mean	9339131	7764796	10718517	9802047	10713007	8922071	9357969	13549094	12214601	12448780	11810051	13936078
	min	9336691	7748170	10717569	9765998	10712572	8893733	9357969	13549094	12196745	12448780	11810051	13929872
	max	9348889	7769117	10727049	9818261	10714023	8929156	9357969	13549094	12233713	12448780	11810051	13940099
	std	5005.954	7830.186	2917.882	22784.1	682.2056	14537.29	0	0	10307.06	0	0	5056.898
	gap	0.1044	0.0556	0.0795	0.1651	0.0095	0.0793	0	0	0.1562	0	0	0.0288
f2	mean	9339741	7762424	10718043	9816058	10712717	8922071	9357969	13549094	12215288	12448780	11810051	13938158
	min	9336691	7750491	10717569	9774200	10712572	8893733	9357969	13549094	12210480	12448780	11810051	13929872
	max	9348889	7769117	10727049	9818261	10714023	8929156	9357969	13549094	12233713	12448780	11810051	13940099
	std	5419.104	8499.847	2119.792	9852.339	446.6084	14537.29	0	0	9479.02	0	0	3985.849
	gap	0.0979	0.0862	0.084	0.0224	0.0122	0.0793	0	0	0.1506	0	0	0.0139
t3	mean	9340350	7758234	10718517	9802457	10712790	8918600	9357969	13549094	12209990	12448780	11810051	13935020
	min	9336691	7748170	10717569	9765998	10712572	8893733	9357969	13549094	12196303	12448780	11810051	13929872
	max	9348889	7769117	10727049	9818261	10714023	8929156	9357969	13549094	12233713	12448780	11810051	13940099
	std	5735.04	9333.396	2917.882	22166.53	531.5703	16546.04	0	0	9911.065	0	0	5212.928
	gap	0.0913	0.1401	0.0795	0.161	0.0115	0.1182	0	0	0.1939	0	0	0.0364
t4	mean	9339131	7761028	10718043	9809039	10713007	8917912	9357969	13549094	12209743	12448780	11810051	13933486
	min	9336691	7748170	10717569	9765998	10712572	8893733	9357969	13549094	12196745	12448780	11810051	13929872
	max	9348889	7769117	10727049	9818261	10714023	8929156	9357969	13549094	12233713	12448780	11810051	13940099
	std	5005.954	9387.702	2119.792	18993.79	682.2056	16369.14	0	0	7626.967	0	0	4980.915
	gap	0.1044	0.1041	0.084	0.0939	0.0095	0.1259	0	0	0.1959	0	0	0.0474

Tables 7 and 8 show that the optimum values are achieved in all runs with all transfer functions for the problems ks8_a – ks_12e, ks_16b-16c, ks_20e-24a, and ks_24c-24e. Therefore, the gap and standard deviation values are 0 for these problems.

The gap metric is considered an appropriate measure for evaluating the performance of the transfer functions, since it summarizes the algorithm's success as the percentage difference between the obtained and the actual optimum values. The gap values produced by the binHOA for the small-scale dataset are presented in Table 9. Table 9 shows that the optimum values are achieved in all runs, meaning that the gap values are 0 with all transfer functions for all problems, except for problem f8 with transfer functions s1 and t3. However, to assess the performance of the transfer functions, only one problem instance is insufficient; therefore, the medium-scale dataset will also be considered.

Table 9. Gap values produced by the binHOA for the small-scale dataset

TF	f1	f2	f3	f4	f5	f6	f7	f8	f9	f10
s1	0	0	0	0	0	0	0	0.0041	0	0
s2	0	0	0	0	0	0	0	0	0	0
s3	0	0	0	0	0	0	0	0	0	0
s4	0	0	0	0	0	0	0	0	0	0
u1	0	0	0	0	0	0	0	0	0	0
u2	0	0	0	0	0	0	0	0	0	0
u3	0	0	0	0	0	0	0	0	0	0
u4	0	0	0	0	0	0	0	0	0	0
z1	0	0	0	0	0	0	0	0	0	0
z2	0	0	0	0	0	0	0	0	0	0
z3	0	0	0	0	0	0	0	0	0	0
z4	0	0	0	0	0	0	0	0	0	0
t1	0	0	0	0	0	0	0	0	0	0
t2	0	0	0	0	0	0	0	0	0	0
t3	0	0	0	0	0	0	0	0.002	0	0
t4	0	0	0	0	0	0	0	0	0	0

The gap values produced by the binHOA for the medium-scale dataset are presented in Tables 10 and 11.

Table 10. Gap values produced by the binHOA for the medium-scale dataset (ks_8a-ks_16c)

TF	ks_8a	ks_8b	ks_8c	ks_8d	ks_8e	ks_12a	ks_12b	ks_12c	ks_12d	ks_12e	ks_16a	ks_16b	ks_16c
s1	0	0	0	0	0	0	0	0	0	0	0.157	0	0
s2	0	0	0	0	0	0	0	0	0	0	0.1691	0	0
s3	0	0	0	0	0	0	0	0	0	0	0.1691	0	0
s4	0	0	0	0	0	0	0	0	0	0	0.2053	0	0
u1	0	0	0	0	0	0	0	0	0	0	0.1691	0	0
u2	0	0	0	0	0	0	0	0	0	0	0.157	0	0
u3	0	0	0	0	0	0	0	0	0	0	0.1691	0	0
u4	0	0	0	0	0	0	0	0	0	0	0.1691	0	0
z1	0	0	0	0	0	0	0	0	0	0	0.1449	0	0
z2	0	0	0	0	0	0	0	0	0	0	0.1207	0	0
z3	0	0	0	0	0	0	0	0	0	0	0.1328	0	0
z4	0	0	0	0	0	0	0	0	0	0	0.0845	0	0
t1	0	0	0	0	0	0	0	0	0	0	0.157	0	0
t2	0	0	0	0	0	0	0	0	0	0	0.1328	0	0
t3	0	0	0	0	0	0.0057	0	0	0	0	0.1811	0	0
t4	0	0	0	0	0	0	0	0	0	0	0.157	0	0

Table 11. Gap values produced by the binHOA for the medium-scale dataset (ks_16d-ks_24e)

TF	ks_16d	ks_16e	ks_20a	ks_20b	ks_20c	ks_20d	ks_20e	ks_24a	ks_24b	ks_24c	ks_24d	ks_24e
s1	0.1044	0.0693	0.084	0.1568	0.0122	0.1061	0	0	0.2183	0	0	0.033
s2	0.0979	0.1328	0.084	0.0715	0.0122	0.0595	0	0	0.1709	0	0	0.0252
s3	0.0913	0.082	0	0.0449	0.0115	0.0672	0	0	0.1804	0	0	0.0291
s4	0.0913	0.1066	0	0.0449	0.0122	0.0672	0	0	0.1614	0	0	0.0103
u1	0.0979	0.0406	0.084	0.0449	0.0129	0.0397	0	0	0.1575	0	0	0.0108
u2	0.0848	0.0382	0.0751	0.0449	0.0108	0.0154	0	0	0.1519	0	0	0.0103
u3	0.0783	0.1058	0	0.0673	0.0115	0.0267	0	0	0.1601	0	0	0.0173
u4	0.1044	0.0867	0	0.0715	0.0088	0.0198	0	0	0.1424	0	0	0.0213
z1	0.0783	0.0421	0	0	0.0115	0.0275	0	0	0.1519	0	0	0.0037
z2	0.0652	0.0502	0	0	0.0108	0	0	0	0.1424	0	0	0.0037
z3	0.0457	0.027	0	0	0	0	0	0	0.1329	0	0	0
z4	0.0652	0.0461	0.0795	0	0.0095	0.0198	0	0	0.1139	0	0	0.0103
t1	0.1044	0.0556	0.0795	0.1651	0.0095	0.0793	0	0	0.1562	0	0	0.0288
t2	0.0979	0.0862	0.084	0.0224	0.0122	0.0793	0	0	0.1506	0	0	0.0139
t3	0.0913	0.1401	0.0795	0.161	0.0115	0.1182	0	0	0.1939	0	0	0.0364
t4	0.1044	0.1041	0.084	0.0939	0.0095	0.1259	0	0	0.1959	0	0	0.0474

The best gap values for each type of transfer function are highlighted with different colors (S-shaped: green, U-shaped: blue, Z-shaped: pink, and T-shaped: orange) in Tables 10 and 11. As seen in Tables 10 and 11, all transfer functions except for t3 achieve the optimum value in all runs for lower-dimensional problem instances (ks_8a-ks_12e). For higher-dimensional problem instances ks_16b-16c, ks_20e-24a, and ks_24c-24d, the

optimum values are achieved with all transfer functions in all runs. Among the S-shaped, U-shaped, and T-shaped transfer functions, s4, u2, and t2 achieved the lowest gap values in 21 out of 25 problems, respectively, while z3 outperformed all other Z-shaped transfer functions by achieving the lowest gap value in 23 out of 25 problems. Overall, z3 demonstrated the best performance among all transfer functions; therefore, the gap values obtained using the binHOA with the z3 transfer function are used for comparison with other algorithms.

In order to evaluate the performance of the algorithms across multiple problems and rank them accordingly, the Friedman test is employed. The Friedman test is a non-parametric statistical method that compares and ranks the performance of more than two algorithms across multiple datasets (Demšar, 2006). The Friedman test results are reported at the bottom of the tables. The gap values produced by the binHOA and the compared algorithms, namely PSO, DE, ABC, GWO, WOA, and SSA, for the small-scale dataset are presented in Table 12.

Table 12. Gap values obtained by the algorithms on the small-scale dataset

	binHOA	PSO	DE	ABC	GWO	WOA	SSA
f1	0	0	0	0	0	0	6.1186
f2	0	0.083	0	0	0	0	1.8311
f3	0	0	0	0	0	0	0
f4	0	0	0	0	0	0	0.2174
f5	0	0	0	0	0	0	8.2732
f6	0	0	0	0	0	0	2.0192
f7	0	0	0	0	0	0	2.4766
f8	0	0.0041	0	0.0036	0.001	0.0015	0.1797
f9	0	0	0	0	0	0	0.4615
f10	0	0.1805	0	0	0	0	1.3951
MeanRank	3.25	4.3	3.25	3.6	3.4	3.5	6.7
Rank	1	5	1	4	2	3	6

Table 13. Gap values obtained by the algorithms on the medium-scale dataset

Gap	binHOA	PSO	DE	ABC	GWO	WOA	SSA
ks_8a	0	0	0	0	0	0	0.97
ks_8b	0	0	0.0406	0	0	0	1.0999
ks_8c	0	0.4894	0.0334	0	0	0	2.1931
ks_8d	0	0	0	0	0	0	1.3531
ks_8e	0	0.1984	0.0992	0	0	0	1.9231
ks_12a	0	0.0255	0.0057	0	0.0057	0	1.2751
ks_12b	0	0.1978	0.0394	0	0	0	1.9365
ks_12c	0	0.0779	0	0	0	0	2.9817
ks_12d	0	0.0455	0	0	0	0	1.8567
ks_12e	0	0.2297	0.1033	0	0	0	3.5616
ks_16a	0.1328	0.1996	0.0242	0.0901	0.0845	0.1449	2.2403
ks_16b	0	0.1416	0.1136	0	0	0	3.0207
ks_16c	0	0.2888	0.0381	0	0	0	3.5639
ks_16d	0.0457	0.2926	0.0867	0.0391	0.0587	0.0783	2.1494
ks_16e	0.027	0.168	0.0096	0.0764	0.121	0.1041	2.6041
ks_20a	0	0.2903	0	0.3015	0.0707	0.084	2.2978
ks_20b	0	0.341	0.0355	0.0266	0.0939	0.0715	2.4728
ks_20c	0	0.4089	0.0076	0.0343	0.0081	0.0115	2.6748
ks_20d	0	0.3837	0.0154	0	0.0154	0.0785	3.0631
ks_20e	0	0.2359	0.0008	0	0	0	2.0923
ks_24a	0	0.3751	0.0995	0	0	0	2.5354
ks_24b	0.1329	0.3182	0.0106	0.4648	0.1253	0.148	2.1391
ks_24c	0	0.3928	0.0405	0	0	0	2.4621
ks_24d	0	0.329	0.0105	0.1931	0	0.0423	2.4899
ks_24e	0	0.2339	0.0068	0.1257	0.0142	0.0215	2.108
MeanRank	2.36	5.6	3.66	3.12	2.96	3.3	7
Rank	1	6	5	3	2	4	7

Table 12 shows that the binHOA and DE algorithms found the optimum values in all runs for all problem instances. The MeanRank and Rank rows denote the Friedman test results and the corresponding rank values, respectively. According to the rank values, the binHOA and DE algorithms outperform the other algorithms. In

contrast, SSA ranked last. The second-ranked algorithm is GWO, with a mean rank value of 3.4. The gap values produced by the binHOA and the compared algorithms, namely PSO, DE, ABC, GWO, WOA, and SSA, for the medium-scale dataset are presented in Table 13.

Table 13 shows that the binHOA found the optimum values in all runs for 21 of the 25 problem instances, thus producing better gap values than the other algorithms for most of the problems. According to the rank values, the binHOA, with a mean rank value of 2.36, outperforms the other algorithms. In contrast, SSA ranked last among the compared algorithms. The second-ranked algorithm is GWO, with a mean rank value of 2.96.

Conclusion

In this study, the recently proposed hiking optimization algorithm is binarized using four different types of transfer functions and the binHOA is proposed. The proposed binHOA is applied to the 0/1 knapsack problem. In addition, to improve the performance of the proposed algorithm, a stochastic repair function is adopted. Initially, the performance of 16 different transfer functions is assessed on small-scale and medium-scale benchmark datasets. The experimental results indicate that the z3 transfer function outperforms the other functions; thus, the results obtained using the z3 transfer function are compared against the binary versions of six well-known algorithms. According to the experimental results, the binHOA outperforms the other algorithms for most of the problem instances in the datasets. The overall experimental results demonstrate that the proposed algorithm serves as a competitive and effective approach for solving the 0/1 knapsack problem.

Recommendations

For future studies, the HOA can be evaluated on large-scale datasets to observe its limitations, and further modifications can be applied to enhance the overall performance of the algorithm.

Scientific Ethics Declaration

* The author declares that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the author.

Conflict of Interest

* The author declares that there is no conflict of interest.

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Author(s) Information

Aybuke Babadag

Konya Technical University
Ardıçlı Mahallesi Rauf Orbay Cd. 42250 Selçuklu/Konya,
Türkiye

ORCID iD: <https://orcid.org/0000-0002-4091-6684>

*Contact e-mail: ababadag@ktun.edu.tr

*Corresponding author(s) email

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Neutrosophic Nano Regular Generalized Star Star B – Continuous and Irresolute Mappings in Neutrosophic Nano Topological Spaces

Raja Mohammad Latif

Prince Mohammad Bin Fahd University

Abstract: Neutrosophic sets, proposed by Smarandache, extend fuzzy sets and intuitionistic fuzzy sets to better manage imprecise, incomplete, and inconsistent information frequently encountered in real-world problems. A neutrosophic set is characterized by three independent components: truth, indeterminacy, and falsity. Based on this framework, Salama introduced the notion of neutrosophic topological spaces. The concept of a Neutrosophic Nano Topological Space further integrates neutrosophic set theory with nano topology to effectively model uncertainty, indeterminacy, and vagueness in highly granular or fine-scale systems and structures. In 2020, N. Rajeshwari, G. Vasanthakannan, and J. Subashini introduced the concepts of neutrosophic nano regular generalized star star b-closed ($N_{cut}N_{ano}rg^{**}b$ -closed) sets and studied some basic properties in neutrosophic nano topological space ($N_{cut}N_{ano}$ -Top-Spaces). In this research paper, we introduce the concepts of $N_{cut}N_{ano}rg^{**}b$ -continuous mappings, $N_{cut}N_{ano}rg^{**}b$ -irresolute mappings, $N_{cut}N_{ano}rg^{**}b$ -closed mappings, $N_{cut}N_{ano}rg^{**}b$ -open mappings, strongly $N_{cut}N_{ano}rg^{**}b$ -continuous mappings, perfectly $N_{cut}N_{ano}rg^{**}b$ -continuous mappings, $N_{cut}N_{ano}contra$ - $rg^{**}b$ -continuous mappings, $N_{cut}N_{ano}contra$ - $rg^{**}b$ -irresolute mappings and totally $N_{cut}N_{ano}rg^{**}b$ -continuous mappings in neutrosophic topological spaces ($N_{cut}N_{ano}$ -Top-Spaces). We investigate and obtain several properties and characterizations concerning these mappings in $N_{cut}N_{ano}$ -Top-Spaces.

Keywords: $N_{cut}N_{ano}rg^{**}b$ -continuous map, $N_{cut}N_{ano}rg^{**}b$ -irresolute map, $N_{cut}N_{ano}rg^{**}b$ -open map, $N_{cut}N_{ano}rg^{**}b$ -closed map, $N_{cut}N_{ano}contra$ - $rg^{**}b$ -irresolute map

Introduction

Many real-world problems inherently involve uncertainty, imprecision, and indeterminacy, particularly in disciplines such as computer science, engineering, artificial intelligence, medical diagnosis, and decision-making. Conventional set theory and topology, which are founded on precise and deterministic information, often fall short in handling such complexities. To address these shortcomings, various mathematical models have been developed, including fuzzy sets proposed by Zadeh (1965), intuitionistic fuzzy sets introduced by Atanassov (1986), rough sets formulated by Pawlak (1982), soft sets by Molodtsov (1999), and neutrosophic sets by Smarandache (1999). These approaches have made substantial contributions to the modeling and analysis of incomplete, inconsistent, and uncertain data. The investigation of $N_{cut}N_{ano}$ -Top-Space is significant from both theoretical and applied perspectives. Theoretically, it expands the framework of topological structures by combining the adaptability of neutrosophic sets with the rigor of nano topology. In practice, $N_{cut}N_{ano}$ -Top-Space demonstrates strong potential for applications such as knowledge representation, data mining, image processing, pattern recognition, and decision-making, where the effective handling of indeterminate and inconsistent information is essential. As a result, $N_{cut}N_{ano}$ -Top-Space provides a robust hybrid framework that fosters new research directions and innovations in environments characterized by uncertainty. In this research paper, we introduce the concepts of $N_{cut}N_{ano}rg^{**}b$ -continuous mappings,

$N_{cut}N_{ano}rg^{**b}$ -irresolute mappings, $N_{cut}N_{ano}rg^{**b}$ -closed mappings, $N_{cut}N_{ano}rg^{**b}$ -open mappings, strongly $N_{cut}N_{ano}rg^{**b}$ -continuous mappings, perfectly $N_{cut}N_{ano}rg^{**b}$ -continuous mappings, $N_{cut}N_{ano}contra-\alpha g\#\psi$ -continuous mappings, $N_{cut}N_{ano}contra-rg^{**b}$ -irresolute mappings and totally $N_{cut}N_{ano}rg^{**b}$ -continuous mappings in $N_{cut}N_{ano}$ -Top-Space. We investigate and obtain several properties and characterizations concerning these mappings in $N_{cut}N_{ano}$ -Top-Spaces.

Preliminaries

Definition 2.1. Let X be a non-empty fixed set. A neutrosophic set (briefly N_{eu} -set) A is an object having a form $A = \{\langle x, T_A(x), Q_A(x), F_A(x) \rangle : x \in X\}$, where $T_A : X \rightarrow [0,1]$, $Q_A : X \rightarrow [0,1]$ and $F_A : X \rightarrow [0,1]$ are the functions such that $T_A(x)$ -represents the truth-membership degree of membership, $Q_A(x)$ - represents the degree of indeterminacy, and $F_A(x)$ - represents the degree of non-membership.

Definition 2.2. Let $A = \{\langle x, T_A(x), Q_A(x), F_A(x) \rangle : x \in X\}$, and $B = \{\langle x, T_B(x), Q_B(x), F_B(x) \rangle : x \in X\}$

1. $0_{NN} = \{\langle x, 0, 0, 1 \rangle : x \in X\}$, $1_{NN} = \{\langle x, 1, 1, 0 \rangle : x \in X\}$
2. Subset : $A \subseteq B \Leftrightarrow T_A(x) \leq T_B(x), Q_A(x) \leq Q_B(x), F_A(x) \geq F_B(x), " x \in X$
3. Equal : $A = B \Leftrightarrow A \subseteq B$ and $B \subseteq A$.
4. Complement (Supplement) : $A^C = \{\langle x, F_A(x), 1 - Q_A(x), T_A(x) \rangle : x \in X\}$,
5. Union : $A \cup B = \{\langle x, \max(T_A(x), T_B(x)), \min(Q_A(x), Q_B(x)), \min(F_A(x), F_B(x)) \rangle : x \in X\}$
6. Intersection : $A \cap B = \{\langle x, \min(T_A(x), T_B(x)), \max(Q_A(x), Q_B(x)), \max(F_A(x), F_B(x)) \rangle : x \in X\}$.

Definition 2.3. A neutrosophic topology on a non-empty X is a family of T_N of neutrosophic sets in X satisfying the following axioms:

- (01) $0_N, 1_N \in T_N$
- (I) " $G, H \in T_N \Rightarrow G \cap H \in T_N$
- (U) " $\{G_\lambda : \lambda \in \Lambda\} \subseteq T_N \Rightarrow \bigcup_{\lambda \in \Lambda} G_\lambda \in T_N$

Definition 2.4. Let U be a non-empty finite set of objects called the universe, and R be an equivalence relation on U named as the indiscernibility relation. Then U is divided into disjoint equivalence classes. Let X be a subset of U . Then the lower approximation of X with respect to R is denoted by $\underline{R} = \bigcup_{x \in U} \{R(x) : R(x) \subseteq X\}$, where $R(x)$ denotes the equivalence class determined by $x \in U$.

Definition 2.5. The upper approximation of X with respect to R is the set of all objects that can be possibly classified as X with respect to R and it is denoted by $\overline{R} = \bigcup_{x \in U} \{R(x) : R(x) \cap X \neq \emptyset\}$.

Definition 2.6. The boundary region of X with respect to R is the set of all objects that can be possibly classified neither as X nor as not X with respect to R and it is denoted by $B_R = \overline{R} - \underline{R}$.

Definition 2.7. Let U be a universe and R be an equivalence relation on U and let S be a neutrosophic subset of U . Then the neutrosophic nano topology

$$\begin{aligned} \Upsilon_{\mathbb{NN}}(S) &= \{0_{\mathbb{NN}}, 1_{\mathbb{NN}}, \overline{\mathbb{N}}(S), \underline{\mathbb{N}}(S), B_N(S)\}, \quad \text{where} \quad \overline{\mathbb{N}}(S) = \left\{ \langle x, M_{\overline{\mathbb{R}}(x)}, I_{\overline{\mathbb{R}}(x)}, N_{\overline{\mathbb{R}}(x)}(x) \rangle : z \in [x]_{\mathbb{R}}, x \in U \right\}. \\ \underline{\mathbb{N}}(S) &= \left\{ \langle x, M_{\underline{\mathbb{R}}(x)}, I_{\underline{\mathbb{R}}(x)}, N_{\underline{\mathbb{R}}(x)}(x) \rangle : z \in [x]_{\mathbb{R}}, x \in U \right\}. \\ B_N(S) &= \overline{\mathbb{N}}(S) - \underline{\mathbb{N}}(S). \quad \text{where} \quad M_{\underline{\mathbb{R}}(x)} = \inf \{M_S(z) : z \in [x]_{\mathbb{R}}\}, \\ I_{\underline{\mathbb{R}}(x)} &= \inf \{I_S(z) : z \in [x]_{\mathbb{R}}\}, \quad N_{\underline{\mathbb{R}}(x)} = \sup \{N_S(z) : z \in [x]_{\mathbb{R}}\}, \quad M_{\overline{\mathbb{R}}(x)} = \sup \{M_S(z) : z \in [x]_{\mathbb{R}}\}, \\ I_{\overline{\mathbb{R}}(x)} &= \sup \{I_S(z) : z \in [x]_{\mathbb{R}}\}, \quad N_{\overline{\mathbb{R}}(x)} = \inf \{N_S(z) : z \in [x]_{\mathbb{R}}\}. \end{aligned}$$

Definition 2.8. Let U be a universe, $\mathbb{R}$ be an equivalence relation on U and S be a neutrosophic set in U and if the collection $\Upsilon_{\mathbb{NN}}(S) = \{0_{\mathbb{NN}}, 1_{\mathbb{NN}}, \underline{\mathbb{N}}(S), \overline{\mathbb{N}}(S), B_N(S)\}$ containing neutrosophic nano subsets of U satisfies the axioms of a topology, namely (i) $0_{\mathbb{NN}}, 1_{\mathbb{NN}} \in \Upsilon_{\mathbb{NN}}(S)$ (ii) $G \cap H \in \Upsilon_{\mathbb{NN}}(S)$ for every $G, H \in \Upsilon_{\mathbb{NN}}(S)$ (iii) $\bigcup_{j \in J} G_j \in \Upsilon_{\mathbb{NN}}(S)$ for every $\{G_j : j \in J\} \subseteq \Upsilon_{\mathbb{NN}}(S)$. Then the pair $(U, \Upsilon_{\mathbb{NN}}(S))$ is called a neutrosophic nano topological space (briefly $N_{\text{eut}}N_{\text{ano}}\text{-Top-Space}$). The elements of $\Upsilon_{\mathbb{NN}}(S)$ are called neutrosophic nano rg**b -open (briefly $N_{\text{eut}}N_{\text{ano}}\text{rg**b-open}$) sets in U . A $N_{\text{eut}}N_{\text{ano}}$ -set A in U is called a neutrosophic nano rg**b -closed (briefly $N_{\text{eut}}N_{\text{ano}}\text{rg**b-closed}$) set if and only if its complement A^C is a $N_{\text{eut}}N_{\text{ano}}\alpha\mathcal{G}\#\psi$ -open set.

Definition 2.9. Let $(U, \Upsilon_{\mathbb{NN}}(S))$ be a $N_{\text{eut}}N_{\text{ano}}\text{-Top-Space}$ and A be a $N_{\text{eut}}N_{\text{ano}}$ -set. Then

- (i) The neutrosophic nano interior of A , denoted by $N_{\text{eut}}N_{\text{ano}}\text{-Int}(A)$ is the union of all $N_{\text{eut}}N_{\text{ano}}$ -open subsets of A . $N_{\text{eut}}N_{\text{ano}}\text{-Int}(A) = \bigcup \{G : G \text{ is a } N_{\text{eut}}N_{\text{ano}}\text{-open set in } U \text{ and } G \subseteq A\}$.
- (ii) The neutrosophic nano closure of A denoted by $N_{\text{eut}}N_{\text{ano}}\text{-Cl}(A)$ is the intersection of all $N_{\text{eut}}N_{\text{ano}}$ -closed sets containing A . $N_{\text{eut}}N_{\text{ano}}\text{-Cl}(A) = \bigcap \{K : K \text{ is a } N_{\text{eut}}N_{\text{ano}}\text{-closed set in } U \text{ and } A \subseteq K\}$.

Definition 2.10. Let A be a $N_{\text{eut}}N_{\text{ano}}$ -subset of a $N_{\text{eut}}N_{\text{ano}}\text{-Top-Space}$ $(U, \Upsilon_{\mathbb{NN}}(S))$. Then A is called

- (i) $N_{\text{eut}}N_{\text{ano}}$ -semi-open if $A \subseteq N_{\text{eut}}N_{\text{ano}}\text{-Cl}(N_{\text{eut}}N_{\text{ano}}\text{-Int}(A))$.
- (ii) $N_{\text{eut}}N_{\text{ano}}\text{-}\alpha$ -open set if $A \subseteq N_{\text{eut}}N_{\text{ano}}\text{-Int}(N_{\text{eut}}N_{\text{ano}}\text{-Cl}(N_{\text{eut}}N_{\text{ano}}\text{-Int}(A)))$.
- (iii) $N_{\text{eut}}N_{\text{ano}}$ -pre-open set if $A \subseteq N_{\text{eut}}N_{\text{ano}}\text{-Int}(N_{\text{eut}}N_{\text{ano}}\text{-Cl}(A))$.
- (iv) $N_{\text{eut}}N_{\text{ano}}$ -sregular-open set if $A = N_{\text{eut}}N_{\text{ano}}\text{-Int}(N_{\text{eut}}N_{\text{ano}}\text{-Cl}(A))$.
- (v) $N_{\text{eut}}N_{\text{ano}}\text{-b}$ -open set if $A \subseteq [N_{\text{eut}}N_{\text{ano}}\text{-Cl}(N_{\text{eut}}N_{\text{ano}}\text{-Int}(A))] \cup [N_{\text{eut}}N_{\text{ano}}\text{-Int}(N_{\text{eut}}N_{\text{ano}}\text{-Cl}(A))]$
- (vi) $N_{\text{eut}}N_{\text{ano}}$ -semi pre open if $A \subseteq N_{\text{eut}}N_{\text{ano}}\text{-Cl}(N_{\text{eut}}N_{\text{ano}}\text{-Int}(N_{\text{eut}}N_{\text{ano}}\text{-Cl}(A)))$.

The complement of the above-mentioned sets are called their respective $N_{\text{eut}}N_{\text{ano}}$ -closed sets.

Definition 2.11. Let A be a $N_{\text{eut}}N_{\text{ano}}$ -subset of a $N_{\text{eut}}N_{\text{ano}}\text{-Top-Space}$ $(U, \Upsilon_{\mathbb{NN}}(S))$. Then A is called a

- (i) $N_{\text{eut}}N_{\text{ano}}$ -generalized-closed (briefly $N_{\text{eut}}N_{\text{ano}}\mathcal{G}$ -closed) set if $N_{\text{eut}}N_{\text{ano}}\text{-Cl}(A) \subseteq V$ whenever $A \subseteq V$ and V is $N_{\text{eut}}N_{\text{ano}}$ -open in $(U, \Upsilon_{\mathbb{NN}}(S))$.
- (ii) $N_{\text{eut}}N_{\text{ano}}$ -generalized-star-closed (briefly $N_{\text{eut}}N_{\text{ano}}\mathcal{G}^*$ -closed) set if $N_{\text{eut}}N_{\text{ano}}\text{-Cl}(A) \subseteq V$ whenever $A \subseteq V$ and V is $N_{\text{eut}}N_{\text{ano}}\mathcal{G}$ -open set in $(U, \Upsilon_{\mathbb{NN}}(S))$.

- (iii) $N_{eut}N_{ano}$ generalized α -closed (briefly $N_{eut}N_{ano}g\alpha$ -closed) set if $N_{eut}N_{ano}\alpha-Cl(A) \subseteq V$ whenever $A \subseteq V$ and V is $N_{eut}N_{ano}\alpha$ -open in $(U, \Upsilon_{NN}(S))$.
- (iv) $N_{eut}N_{ano}$ generalized p -pre-closed (briefly $N_{eut}N_{ano}gp$ -closed) set if $N_{eut}N_{ano}p-Cl(A) \subseteq V$ whenever $A \subseteq V$ and V is $N_{eut}N_{ano}$ -open in $(U, \Upsilon_{NN}(S))$.
- (v) $N_{eut}N_{ano}$ generalized p -regular closed (briefly $N_{eut}N_{ano}gpr$ -closed) set if $N_{eut}N_{ano}p-Cl(A) \subseteq V$ whenever $A \subseteq V$ and V is $N_{eut}N_{ano}$ -regular open in $(U, \Upsilon_{NN}(S))$.
- (vi) $N_{eut}N_{ano}$ regular generalized $\star$ -closed (briefly $N_{eut}N_{ano}rg\star$ -closed) set if $N_{eut}N_{ano}\star-Cl(A) \subseteq V$ whenever $A \subseteq V$ and V is $N_{eut}N_{ano}$ -regular open in $(U, \Upsilon_{NN}(S))$.
- (vii) $N_{eut}N_{ano}$ regular generalized $\star$ -b closed (briefly $N_{eut}N_{ano}rg\star b$ -closed) set if $N_{eut}N_{ano}b-Cl(A) \subseteq V$ whenever $A \subseteq V$ and V is $N_{eut}N_{ano}rg\star$ -open in $(U, \Upsilon_{NN}(S))$.

Definition 2.12. Let $(U, \Upsilon_{NN}(S))$ be a $N_{eut}N_{ano}$ -Top-Space and A be a $N_{eut}N_{ano}$ -set of U . Then A is said to be a Neutrosophic Nano regular generalized star star b - closed (briefly $N_{eut}N_{ano}rg\star\star b$ -closed) set if $N_{eut}N_{ano}rg\star\star b-Cl(A) \subseteq V$ whenever $A \subseteq V$ and V is $N_{eut}N_{ano}$ -open in $(U, \Upsilon_{NN}(S))$.

Definition 2.13. Let $(U, \Upsilon_{NN}(S))$ be a $N_{eut}N_{ano}$ -Top-Space and A be a $N_{eut}N_{ano}$ -set of U . Then A is said to be a Neutrosophic Nano regular generalized star star b - open (briefly $N_{eut}N_{ano}rg\star\star b$ -open) set if its complement A^c is $N_{eut}N_{ano}rg\star\star b$ -closed in $(U, \Upsilon_{NN}(S))$.

The collection of all $N_{eut}N_{ano}rg\star\star b$ -open (resp. $N_{eut}N_{ano}rg\star\star b$ -closed) sets in a $N_{eut}N_{ano}$ -Top-Space $(U, \Upsilon_{NN}(S))$ is denoted by $N_{eut}N_{ano}rg\star\star b-O(U, \Upsilon_{NN}(S))$ [*resp.* $N_{eut}N_{ano}rg\star\star b-C(U, \Upsilon_{NN}(S))$].

Theorem 2.14. In a $N_{eut}N_{ano}$ -Top-Space $(U, \Upsilon_{NN}(S))$, we have the following conditions.

- (i) 0_{NN} and 1_{NN} are $N_{eut}N_{ano}rg\star\star b$ -open and $N_{eut}N_{ano}rg\star\star b$ -closed sets in $(U, \Upsilon_{NN}(S))$.
- (ii) The Union of two $N_{eut}N_{ano}rg\star\star b$ -closed sets in $(U, \Upsilon_{NN}(S))$ is $N_{eut}N_{ano}rg\star\star b$ -closed set.
- (iii) The Intersection of two $N_{eut}N_{ano}rg\star\star b$ -open sets in $(U, \Upsilon_{NN}(S))$ is $N_{eut}N_{ano}rg\star\star b$ -open

Definition 2.15. A $N_{eut}N_{ano}$ -set A in a $N_{eut}N_{ano}$ -Top-Space $(U, \Upsilon_{NN}(S))$ is called a $N_{eut}N_{ano}rg\star\star b$ -interior of A (briefly $N_{eut}N_{ano}rg\star\star b-Int(A)$) and $N_{eut}N_{ano}rg\star\star b$ -closure of A (briefly $N_{eut}N_{ano}rg\star\star b-Cl(A)$) are defined as follows:

- (i) $N_{eut}N_{ano}rg\star\star b-Int(A) = \bigcup \{G : G \text{ is a } N_{eut}N_{ano}rg\star\star b\text{-open set in } U \text{ and } G \subseteq A\}$.
- (ii) $N_{eut}N_{ano}rg\star\star b-Cl(A) = \bigcap \{K : K \text{ is a } N_{eut}N_{ano}rg\star\star b\text{-closed set in } U \text{ and } A \subseteq K\}$.

Theorem 2.16. Every $N_{eut}N_{ano}$ -closed set is $N_{eut}N_{ano}rg\star\star b$ -closed set.

Theorem 2.17. Every $N_{eut}N_{ano}$ -Regular-closed set is $N_{eut}N_{ano}rg\star\star b$ -closed set.

Theorem 2.18. Every $N_{eut}N_{ano}\alpha$ -closed set is $N_{eut}N_{ano}rg\star\star b$ -closed set.

Theorem 2.19. Every $N_{eut}N_{ano}g$ -closed set is $N_{eut}N_{ano}rg\star\star b$ -closed set.

Theorem 2.20. Every $N_{eut}N_{ano}g\star$ -closed set is $N_{eut}N_{ano}rg\star\star b$ -closed set.

Theorem 2.21. Every $N_{eut}N_{ano}g\alpha$ -closed set is $N_{eut}N_{ano}rg^{**}b$ -closed set.

Theorem 2.22. Let $(U, \Upsilon_{NN}(S))$ be a $N_{eut}N_{ano}$ -Top-Space. Then for any $N_{eut}N_{ano}$ -subsets A and B of U , the following statements are true.

- (i) $N_{eut}N_{ano}rg^{**}b-Int(A) \subseteq A \subseteq N_{eut}N_{ano}rg^{**}b-Cl(A)$.
- (ii) A is $N_{eut}N_{ano}rg^{**}b$ -open set in U if and only if $N_{eut}N_{ano}rg^{**}b-Int(A) = A$.
- (iii) A is $N_{eut}N_{ano}rg^{**}b$ -closed set in U if and only if $N_{eut}N_{ano}rg^{**}b-Cl(A) = A$.
- (iv) $N_{eut}N_{ano}rg^{**}b-Int[N_{eut}N_{ano}rg^{**}b-Int(A)] = N_{eut}N_{ano}rg^{**}b-Int(A)$.
- (v) $N_{eut}N_{ano}rg^{**}b-Cl[N_{eut}N_{ano}rg^{**}b-Cl(A)] = N_{eut}N_{ano}rg^{**}b-Cl(A)$.
- (vi) If $A \subseteq B$, then $N_{eut}N_{ano}rg^{**}b-Int(A) \subseteq N_{eut}N_{ano}rg^{**}b-Int(B)$
- (vii) If $A \subseteq B$, then $N_{eut}N_{ano}rg^{**}b-Cl(A) \subseteq N_{eut}N_{ano}rg^{**}b-Cl(B)$
- (viii) $(N_{eut}N_{ano}rg^{**}b-Cl(A))^C = N_{eut}N_{ano}rg^{**}b-Int(A^C)$
- (iX) $(N_{eut}N_{ano}rg^{**}b-Int(A))^C = N_{eut}N_{ano}rg^{**}b-Cl(A^C)$
- (X) $N_{eut}N_{ano}rg^{**}b-Int(0_{NN}) = 0_{NN}$, $N_{eut}N_{ano}rg^{**}b-Int(1_{NN}) = 1_{NN}$.
- (Xi) $N_{eut}N_{ano}rg^{**}b-Cl(0_{NN}) = 0_{NN}$, $N_{eut}N_{ano}rg^{**}b-Cl(1_{NN}) = 1_{NN}$
- (Xiii) $N_{eut}N_{ano}rg^{**}b-Int(A \cap B) \subseteq [N_{eut}N_{ano}rg^{**}b-Int(A)] \cap [N_{eut}N_{ano}rg^{**}b-Int(B)]$
- (Xiv) $N_{eut}N_{ano}rg^{**}b-Cl(A) \cup N_{eut}N_{ano}rg^{**}b-Cl(B) \subseteq N_{eut}N_{ano}rg^{**}b-Cl(A \cup B)$
- (Xv) $[N_{eut}N_{ano}rg^{**}b-Int(A)] \cup [N_{eut}N_{ano}rg^{**}b-Int(B)] \subseteq N_{eut}N_{ano}rg^{**}b-Int(A \cup B)$
- (Xvi) $N_{eut}N_{ano}rg^{**}b-Cl(A \cap B) \subseteq [N_{eut}N_{ano}rg^{**}b-Cl(A)] \cap [N_{eut}N_{ano}rg^{**}b-Cl(B)]$

Definition 2.23. A map $\xi: (U, \Upsilon_{NN}(S)) \rightarrow (W, \Gamma_{NN}(T))$ is called a $N_{eut}N_{ano}$ -continuous mapping if $\xi^{-1}(B)$ is a $N_{eut}N_{ano}$ -open (resp. $N_{eut}N_{ano}$ -closed) set in U , for every $N_{eut}N_{ano}$ -open (resp. $N_{eut}N_{ano}$ -closed) set B in W .

3. Neutrosophic Nano Regular Generalized Star Star b-Continuous Mappings

In this section, we introduce the concepts of neutrosophic nano regular generalized star star b-continuous ($N_{eut}N_{ano}rg^{**}b$ -continuous) mappings in $N_{eut}N_{ano}$ -Top-Spaces. Also, we study some of the main results depending on $N_{eut}N_{ano}rg^{**}b$ -open sets.

Definition 3.1. A map $\xi: (U, \Upsilon_{NN}(S)) \rightarrow (W, \Gamma_{NN}(T))$ is called a $N_{eut}N_{ano}rg^{**}b$ -continuous function if $\xi^{-1}(B)$ is a $N_{eut}N_{ano}rg^{**}b$ -open (resp. $N_{eut}N_{ano}rg^{**}b$ -closed) set in U , for every $N_{eut}N_{ano}$ -open (resp. $N_{eut}N_{ano}$ -closed) set B in W .

Theorem 3.2. Every $N_{eut}N_{ano}$ -continuous mapping is $N_{eut}N_{ano}rg^{**}b$ -continuous mapping.

Proof. Let $\xi: (U, \Upsilon_{NN}(S)) \rightarrow (W, \Gamma_{NN}(T))$ be a $N_{eut}N_{ano}$ -continuous mapping. Let H be a $N_{eut}N_{ano}$ -open set in $(W, \Gamma_{NN}(T))$. Then $\xi^{-1}(H)$ is $N_{eut}N_{ano}$ -open set in $(U, \Upsilon_{NN}(S))$. Since every

$N_{\text{cut}}N_{\text{ano}}$ -open set is $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -open, $\xi^{-1}(H)$ is $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -open set in $(U, \Upsilon_{\text{NN}}(S))$. Hence ξ is $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -continuous mapping.

Theorem 3.3. Let $(U, \Upsilon_{\text{NN}}(S))$, $(W, \Gamma_{\text{NN}}(T))$ and $(Z, \Psi_{\text{NN}}(T^*))$ be $N_{\text{cut}}N_{\text{ano}}$ -Top-Spaces. If $\xi: (U, \Upsilon_{\text{NN}}(S)) \rightarrow (W, \Gamma_{\text{NN}}(T))$ is a $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -continuous mapping and $\eta: (W, \Gamma_{\text{NN}}(T)) \rightarrow (Z, \Psi_{\text{NN}}(T^*))$ is $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -continuous, then $\eta \circ \xi: (U, \Upsilon_{\text{NN}}(S)) \rightarrow (Z, \Psi_{\text{NN}}(T^*))$ is a $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -continuous mapping.

Proof. Let G be a $N_{\text{cut}}N_{\text{ano}}$ -open set in Z . Since $\eta: (W, \Gamma_{\text{NN}}(T)) \rightarrow (Z, \Psi_{\text{NN}}(T^*))$ is $N_{\text{cut}}N_{\text{ano}}$ -continuous, $\eta^{-1}(G)$ is $N_{\text{cut}}N_{\text{ano}}$ -open in W . Since ξ is a $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -continuous mapping, $\xi^{-1}[\eta^{-1}(G)]$ is $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -open in U . But $\xi^{-1}[\eta^{-1}(G)] = (\eta \circ \xi)^{-1}(G)$. Then $(\eta \circ \xi)^{-1}(G)$ is $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -open set in U . Hence, $\eta \circ \xi$ is a $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -continuous mapping.

Theorem 3.4. Let $(U, \Upsilon_{\text{NN}}(S))$ and $(W, \Gamma_{\text{NN}}(T))$ be two $N_{\text{cut}}N_{\text{ano}}$ -Top-Spaces. Then prove that $\xi: (U, \Upsilon_{\text{NN}}(S)) \rightarrow (W, \Gamma_{\text{NN}}(T))$ is $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -continuous if and only if $\xi^{-1}(B)$ is $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -closed set in U for every $N_{\text{cut}}N_{\text{ano}}$ -closed set B in W .

Proof. Let B be a $N_{\text{cut}}N_{\text{ano}}$ -closed set in W . Then B^C is $N_{\text{cut}}N_{\text{ano}}$ -open set in W . Since ξ is $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -continuous. Therefore $\xi^{-1}(B^C)$ is a $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -open set in U . Since $\xi^{-1}(B^C) = [\xi^{-1}(B)]^C$, $\xi^{-1}(B)$ is $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -closed set in U .

Conversely, Let B be a $N_{\text{cut}}N_{\text{ano}}$ -open set in W . Then B^C is $N_{\text{cut}}N_{\text{ano}}$ -closed set in W . By assumption $\xi^{-1}(B^C)$ is $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -closed set in U . Since $\xi^{-1}(B^C) = [\xi^{-1}(B)]^C$, $\xi^{-1}(B)$ is $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -open set in U . Hence ξ is $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -continuous.

Theorem 3.5. Let $(U, \mathfrak{I}_{\text{NN}}(S))$ and $(W, \Omega_{\text{NN}}(T))$ be two $N_{\text{cut}}N_{\text{ano}}$ -Top-Spaces and $\xi: U \rightarrow W$ be a mapping. Then ξ is a $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -continuous mapping if and only if $\xi(N_{\text{cut}}N_{\text{ano}}rg^{**}b\text{-Cl}(P)) \subseteq N_{\text{trs}}N_{\text{n}}\text{-Cl}(\xi(P))$ for every $N_{\text{cut}}N_{\text{ano}}$ -set P in U .

Proof. Let P be a $N_{\text{cut}}N_{\text{ano}}$ -set in U and ξ be a $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -continuous mapping. We note that evidently $\xi(P) \subseteq N_{\text{cut}}N_{\text{ano}}rg^{**}b\text{-Cl}[\xi(P)]$. Then we obtain $P \subseteq \xi^{-1}[\xi(P)] \subseteq \xi^{-1}[N_{\text{cut}}N_{\text{ano}}rg^{**}b\text{-Cl}(\xi(P))]$ and $N_{\text{cut}}N_{\text{ano}}rg^{**}b\text{-Cl}(P) \subseteq N_{\text{cut}}N_{\text{ano}}rg^{**}b\text{-Cl}[\xi^{-1}(N_{\text{cut}}N_{\text{ano}}rg^{**}b\text{-Cl}(\xi(P)))]$. Since ξ is a $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -continuous mapping and $N_{\text{cut}}N_{\text{ano}}rg^{**}b\text{-Cl}[\xi(P)]$ is a $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -closed set. Thus we have $N_{\text{cut}}N_{\text{ano}}rg^{**}b\text{-Cl}[\xi^{-1}(N_{\text{cut}}N_{\text{ano}}rg^{**}b\text{-Cl}(\xi(P)))] = \xi^{-1}[N_{\text{cut}}N_{\text{ano}}rg^{**}b\text{-Cl}(\xi(P))]$. Hence, we have $\xi[N_{\text{cut}}N_{\text{ano}}rg^{**}b\text{-Cl}(P)] \subseteq N_{\text{cut}}N_{\text{ano}}\text{-Cl}[\xi(P)]$.

Conversely, let $\xi[N_{\text{cut}}N_{\text{ano}}rg^{**}b\text{-Cl}(P)] \subseteq N_{\text{cut}}N_{\text{ano}}\text{-Cl}[\xi(P)]$, for each $N_{\text{trs}}N_{\text{n}}$ -set P in U . Let Q be a $N_{\text{trs}}N_{\text{n}}$ -closed set in W . Then $N_{\text{cut}}N_{\text{ano}}rg^{**}b\text{-Cl}[\xi^{-1}(Q)] \subseteq N_{\text{cut}}N_{\text{ano}}rg^{**}b\text{-Cl}(Q) = Q$. By assumption, $\xi[N_{\text{cut}}N_{\text{ano}}rg^{**}b\text{-Cl}(\xi^{-1}(Q))] \subseteq N_{\text{cut}}N_{\text{ano}}\text{-Cl}[\xi(\xi^{-1}(Q))] \subseteq Q$ and so

$N_{\text{eut}}N_{\text{ano}}rg^{**}b\text{-Cl}[\xi^{-1}(Q)] \subseteq \xi^{-1}(Q)$. Since $\xi^{-1}(Q) \subseteq N_{\text{eut}}N_{\text{ano}}rg^{**}b\text{-Cl}[\xi^{-1}(Q)]$. Thus we have $N_{\text{eut}}N_{\text{ano}}rg^{**}b\text{-Cl}[\xi^{-1}(Q)] = \xi^{-1}(Q)$. This implies that $\xi^{-1}(Q)$ is a $N_{\text{eut}}N_{\text{ano}}rg^{**}b\text{-closed}$ set in U . Therefore by Theorem 3.4, ξ is a $N_{\text{eut}}N_{\text{ano}}rg^{**}b\text{-continuous}$ mapping.

Theorem 3.6. Let $\xi : (U, \mathfrak{T}_{NN}(S)) \rightarrow (W, \Omega_{NN}(S^*))$ be a mapping. Then ξ is a $N_{\text{eut}}N_{\text{ano}}rg^{**}b\text{-continuous}$ mapping if and only if $N_{\text{eut}}N_{\text{ano}}rg^{**}b\text{-Cl}[\xi^{-1}(Q)] \subseteq \xi^{-1}[N_{\text{eut}}N_{\text{ano}}\text{-Cl}(Q)]$ for each $N_{\text{eut}}N_{\text{ano}}\text{-set}$ Q in W .

Proof. Suppose that $\xi : (U, \mathfrak{T}_{NN}(S)) \rightarrow (W, \Omega_{NN}(S^*))$ is a $N_{\text{eut}}N_{\text{ano}}rg^{**}b\text{-continuous}$ mapping. Take Q be any $N_{\text{eut}}N_{\text{ano}}\text{-set}$ in W . Clearly $Q \subseteq N_{\text{eut}}N_{\text{ano}}\text{-Cl}(Q)$ implies $\xi^{-1}(Q) \subseteq \xi^{-1}[N_{\text{eut}}N_{\text{ano}}rg^{**}b\text{-Cl}(Q)]$. Then $N_{\text{eut}}N_{\text{ano}}rg^{**}b\text{-Cl}[\xi^{-1}(Q)] \subseteq N_{\text{eut}}N_{\text{ano}}rg^{**}b\text{-Cl}[\xi^{-1}(N_{\text{eut}}N_{\text{ano}}\text{-Cl}(Q))]$. Since $N_{\text{eut}}N_{\text{ano}}\text{-Cl}(Q)$ is $N_{\text{eut}}N_{\text{ano}}\text{-closed}$ set in W . So by Theorem 3.4, $\xi^{-1}[N_{\text{eut}}N_{\text{ano}}\text{-Cl}(Q)]$ is a $N_{\text{eut}}N_{\text{ano}}rg^{**}b\text{-closed}$ set in U . Therefore, $N_{\text{eut}}N_{\text{ano}}rg^{**}b\text{-Cl}[\xi^{-1}(N_{\text{eut}}N_{\text{ano}}\text{-Cl}(Q))] = \xi^{-1}[N_{\text{eut}}N_{\text{ano}}\text{-Cl}(Q)]$. Hence, we have $N_{\text{eut}}N_{\text{ano}}rg^{**}b\text{-Cl}[\xi^{-1}(Q)] \subseteq \xi^{-1}[N_{\text{eut}}N_{\text{ano}}\text{-Cl}(Q)]$.

Conversely, let $N_{\text{eut}}N_{\text{ano}}rg^{**}b\text{-Cl}[\xi^{-1}(Q)] \subseteq \xi^{-1}[N_{\text{eut}}N_{\text{ano}}\text{-Cl}(Q)]$ for all $N_{\text{eut}}N_{\text{ano}}\text{-sets}$ Q in W . Let F be a $N_{\text{eut}}N_{\text{ano}}\text{-closed}$ set in W . Since every $N_{\text{eut}}N_{\text{ano}}\text{-closed}$ set is $N_{\text{eut}}N_{\text{ano}}rg^{**}b\text{-closed}$ set, $N_{\text{eut}}N_{\text{ano}}rg^{**}b\text{-Cl}[\xi^{-1}(F)] \subseteq \xi^{-1}[N_{\text{eut}}N_{\text{ano}}\text{-Cl}(F)] = \xi^{-1}(F)$. This implies that $\xi^{-1}(F)$ is a $N_{\text{eut}}N_{\text{ano}}rg^{**}b\text{-closed}$ set in U . Thus by Theorem 3.4, ξ is a $N_{\text{eut}}N_{\text{ano}}rg^{**}b\text{-continuous}$ mapping.

Theorem 3.7. Let $(U, \Upsilon_{NN}(S))$ and $(W, \Gamma_{NN}(T))$ be two $N_{\text{eut}}N_{\text{ano}}\text{-Top-Spaces}$ and $\xi : U \rightarrow W$ be a mapping.. Then ξ is a $N_{\text{eut}}N_{\text{ano}}rg^{**}b\text{-continuous}$ mapping if and only if $\xi^{-1}[N_{\text{eut}}N_{\text{ano}}\text{-Int}(B)] \subseteq N_{\text{eut}}N_{\text{ano}}rg^{**}b\text{-Int}[\xi^{-1}(B)]$ for every $N_{\text{eut}}N_{\text{ano}}\text{-set}$ B in W .

Proof. Let B be any $N_{\text{eut}}N_{\text{ano}}\text{-set}$ in W and ξ be a $N_{\text{eut}}N_{\text{ano}}rg^{**}b\text{-continuous}$ mapping. Then $N_{\text{eut}}N_{\text{ano}}\text{-Int}(B) \subseteq B$ implies $\xi^{-1}[N_{\text{eut}}N_{\text{ano}}\text{-Int}(B)] \subseteq \xi^{-1}(B)$. Therefore we obtain $N_{\text{eut}}N_{\text{ano}}rg^{**}b\text{-Int}[\xi^{-1}(N_{\text{eut}}N_{\text{ano}}\text{-Int}(B))] \subseteq N_{\text{eut}}N_{\text{ano}}rg^{**}b\text{-Int}[\xi^{-1}(B)]$. Since $N_{\text{eut}}N_{\text{ano}}\text{-Int}(B)$ is $N_{\text{eut}}N_{\text{ano}}\text{-open}$ set in W and ξ is $N_{\text{eut}}N_{\text{ano}}rg^{**}b\text{-continuous}$, $\xi^{-1}[N_{\text{eut}}N_{\text{ano}}\text{-Int}(B)]$ is $N_{\text{eut}}N_{\text{ano}}rg^{**}b\text{-open}$ set in U . So $N_{\text{eut}}N_{\text{ano}}rg^{**}b\text{-Int}[\xi^{-1}(N_{\text{eut}}N_{\text{ano}}\text{-Int}(B))] = \xi^{-1}[N_{\text{eut}}N_{\text{ano}}\text{-Int}(B)] \subseteq N_{\text{eut}}N_{\text{ano}}rg^{**}b\text{-Int}[\xi^{-1}(B)]$.

Conversely, let $\xi^{-1}[N_{\text{eut}}N_{\text{ano}}rg^{**}b\text{-Int}(B)] \subseteq N_{\text{eut}}N_{\text{ano}}rg^{**}b\text{-Int}[\xi^{-1}(B)]$ for every $N_{\text{eut}}N_{\text{ano}}\text{-set}$ B in W . Let G be any $N_{\text{eut}}N_{\text{ano}}\text{-open}$ set in W and hence $N_{\text{eut}}N_{\text{ano}}\text{-Int}(G) = G$. By hypothesis, we have $\xi^{-1}[N_{\text{eut}}N_{\text{ano}}\text{-Int}(G)] \subseteq N_{\text{eut}}N_{\text{ano}}rg^{**}b\text{-Int}[\xi^{-1}(G)]$. Therefore, $\xi^{-1}(G) \subseteq N_{\text{eut}}N_{\text{ano}}rg^{**}b\text{-Int}[\xi^{-1}(G)]$. Also $N_{\text{eut}}N_{\text{ano}}rg^{**}b\text{-Int}[\xi^{-1}(G)] \subseteq \xi^{-1}(G)$. So $N_{\text{eut}}N_{\text{ano}}rg^{**}b\text{-Int}[\xi^{-1}(G)] = \xi^{-1}(G)$. This implies that $\xi^{-1}(G)$ is $N_{\text{eut}}N_{\text{ano}}rg^{**}b\text{-open}$ set in U . Hence ξ is a $N_{\text{eut}}N_{\text{ano}}rg^{**}b\text{-continuous}$ mapping.

Definition 3.8. Let $x_{(r,t,s)}$ be a $N_{\text{cut}}N_{\text{ano}}$ -point of a $N_{\text{cut}}N_{\text{ano}}$ -Top-Space $(U, \Upsilon_{\text{NN}}(S))$. A $N_{\text{cut}}N_{\text{ano}}$ -set A of U is called $N_{\text{cut}}N_{\text{ano}}$ -neighbourhood of $x_{(r,t,s)}$ if there exists a $N_{\text{cut}}N_{\text{ano}}$ -open set B such that $x_{(r,t,s)} \in B \subseteq A$.

Theorem 3.9. Let ξ be a mapping from a $N_{\text{cut}}N_{\text{ano}}$ -Top-Space $(U, \Upsilon_{\text{NN}}(S))$ to a $N_{\text{cut}}N_{\text{ano}}$ -Top-Space $(W, \Gamma_{\text{NN}}(T))$. Then the following assertions are equivalent.

- (i) ξ is $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -continuous.
- (ii) For each $N_{\text{cut}}N_{\text{ano}}$ -point $x_{(r,t,s)} \in U$ and every $N_{\text{cut}}N_{\text{ano}}$ -neighbourhood A of $\xi(x_{(r,t,s)})$, there exists a $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -open set B such that $x_{(r,t,s)} \in B \subseteq \xi^{-1}(A)$.
- (iii) For each $N_{\text{cut}}N_{\text{ano}}$ -point $x_{(r,t,s)} \in U$ and every $N_{\text{cut}}N_{\text{ano}}$ -neighbourhood A of $\xi(x_{(r,t,s)})$, there exists a $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -open set B in U such that $x_{(r,t,s)} \in B$ and $\xi(B) \subseteq A$.

Proof. (i) $\Rightarrow$ (ii): Let $x_{(r,t,s)} \in U$ be a $N_{\text{cut}}N_{\text{ano}}$ -point in U and let A be a $N_{\text{cut}}N_{\text{ano}}$ -neighbourhood of $\xi(x_{(r,t,s)})$ in W such that $\xi(x_{(r,t,s)}) \in B \subseteq A$. Since ξ is $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -continuous, we know that $\xi^{-1}(B)$ is a $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -open set in U and $x_{(r,t,s)} \in \xi^{-1}(B) \subseteq \xi^{-1}(A)$. This implies (ii) is true.

(ii) $\Rightarrow$ (iii): Let $x_{(r,t,s)}$ be a $N_{\text{cut}}N_{\text{ano}}$ -point in U and let A be a $N_{\text{cut}}N_{\text{ano}}$ -neighbourhood of $\xi(x_{(r,t,s)})$. The condition (ii) implies that there exists a $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -open set B in U such that $x_{(r,t,s)} \in B \subseteq \xi^{-1}(A)$. Thus $x_{(r,t,s)} \in B$ and $\xi(B) \subseteq \xi[\xi^{-1}(A)] \subseteq A$. Hence (iii) is true.

(iii) $\Rightarrow$ (i): Let B be a $N_{\text{cut}}N_{\text{ano}}$ -open set in W and let $x_{(r,t,s)} \in \xi^{-1}(B)$. Since B is $N_{\text{cut}}N_{\text{ano}}$ -open set, $\xi(x_{(r,t,s)}) \in B$, and so B is $N_{\text{cut}}N_{\text{ano}}$ -neighbourhood of $\xi(x_{(r,t,s)})$. It follows from (iii) that there exists a $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -open set A in U such that $x_{(r,t,s)} \in A$ and $\xi(A) \subseteq B$ so that $x_{(r,t,s)} \in A \subseteq \xi^{-1}[\xi(A)] \subseteq \xi^{-1}(B)$. This implies by definition that $\xi^{-1}(B)$ is a $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -open set in U . Therefore, ξ is a $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -continuous mapping.

Definition 3.10. Let $x_{(r,t,s)}$ be a $N_{\text{cut}}N_{\text{ano}}$ -point of a $N_{\text{cut}}N_{\text{ano}}$ -Top-Space $(U, \Upsilon_{\text{NN}}(S))$. A $N_{\text{cut}}N_{\text{ano}}$ -set A of U is called $N_{\text{cut}}N_{\text{ano}}$ -neighbourhood of $x_{(r,t,s)}$ if there exists a $N_{\text{cut}}N_{\text{ano}}$ -open set B such that $x_{(r,t,s)} \in B \subseteq A$.

Theorem 3.11. Let ξ be a mapping from a $N_{\text{cut}}N_{\text{ano}}$ -Top-Space $(U, \Upsilon_{\text{NN}}(S))$ to a $N_{\text{cut}}N_{\text{ano}}$ -Top-Space $(W, \Gamma_{\text{NN}}(T))$. Then the following assertions are equivalent.

- (i) ξ is $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -continuous.
- (ii) For each $N_{\text{cut}}N_{\text{ano}}$ -point $x_{(r,t,s)} \in U$ and every $N_{\text{cut}}N_{\text{ano}}$ -neighbourhood A of $\xi(x_{(r,t,s)})$, there exists a $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -open set B such that $x_{(r,t,s)} \in B \subseteq \xi^{-1}(A)$.

(iii) For each $N_{\text{cut}}N_{\text{ano}}$ -point $x_{(r,t,s)} \in U$ and every $N_{\text{cut}}N_{\text{ano}}$ -neighbourhood A of $\xi(x_{(r,t,s)})$, there exists a $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -open set B in U such that $x_{(r,t,s)} \in B$ and $\xi(B) \subseteq A$.

Proof. (i) $\Rightarrow$ (ii): Let $x_{(r,t,s)} \in U$ be a $N_{\text{cut}}N_{\text{ano}}$ -point in U and let A be a $N_{\text{cut}}N_{\text{ano}}$ -neighbourhood of $\xi(x_{(r,t,s)})$. Then there exists a $N_{\text{cut}}N_{\text{ano}}$ -open set B in W such that $\xi(x_{(r,t,s)}) \in B \subseteq A$. Since ξ is $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -continuous, we know that $\xi^{-1}(B)$ is a $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -open set in U and $x_{(r,t,s)} \in \xi^{-1}(B) \subseteq \xi^{-1}(A)$. This implies (ii) is true.

(ii) $\Rightarrow$ (iii): Let $x_{(r,t,s)}$ be a $N_{\text{cut}}N_{\text{ano}}$ -point in U and let A be a $N_{\text{cut}}N_{\text{ano}}$ -neighbourhood of $\xi(x_{(r,t,s)})$. The condition (ii) implies that there exists a $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -open set B in U such that $x_{(r,t,s)} \in B \subseteq \xi^{-1}(A)$. Thus $x_{(r,t,s)} \in B$ and $\xi(B) \subseteq \xi[\xi^{-1}(A)] \subseteq A$. Hence (iii) is true.

(iii) $\Rightarrow$ (i): Let B be a $N_{\text{cut}}N_{\text{ano}}$ -open set in W and let $x_{(r,t,s)} \in \xi^{-1}(B)$. Since B is $N_{\text{cut}}N_{\text{ano}}$ -open set, $\xi(x_{(r,t,s)}) \in B$, and so B is $N_{\text{cut}}N_{\text{ano}}$ -neighbourhood of $\xi(x_{(r,t,s)})$. It follows from (iii) that there exists a $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -open set A in U such that $x_{(r,t,s)} \in A$ and $\xi(A) \subseteq B$ so that $x_{(r,t,s)} \in A \subseteq \xi^{-1}[\xi(A)] \subseteq \xi^{-1}(B)$. This implies by definition that $\xi^{-1}(B)$ is a $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -open set in U .

Therefore ξ is $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -continuous.

4. Neutrosophic Nan Regular Generalized Star Star B-Irresolute Maps

In this section, we introduce the concept of neutrosophic nano $\alpha\mathcal{G}\#\psi$ -irresolute ($N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -irresolute) mappings in $N_{\text{cut}}N_{\text{ano}}$ -Top-Spaces. Also, we discuss the relationship with $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -continuous mappings.

Definition 4.1. A map $\xi: (U, \Upsilon_{\text{NN}}(S)) \rightarrow (W, \Gamma_{\text{NN}}(T))$ is called a $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -irresolute function if $\xi^{-1}(B)$ is a $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -open set in U , for every $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -open set B in W .

Theorem 4.2. Let $(U, \Upsilon_{\text{NN}}(S))$ and $(W, \Gamma_{\text{NN}}(T))$ be two $N_{\text{cut}}N_{\text{ano}}$ -Top-Spaces. Prove that a mapping $\xi: U \rightarrow W$ is $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -irresolute if the inverse image of every $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -closed set in W is $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -closed set in U .

Proof. Let A be any $N_{\text{cut}}N_{\text{ano}}\alpha\mathcal{G}\#\psi$ -closed set in W . Then A^c is $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -open set in W . Since ξ is $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -irresolute, $\xi^{-1}(A^c)$ is $N_{\text{cut}}N_{\text{ano}}\alpha\mathcal{G}\#\psi$ -open set in U and $\xi^{-1}(A^c) = [\xi^{-1}(A)]^c$ which implies that $\xi^{-1}(A)$ is $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -closed set in U .

Conversely, Let B be any $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -open set in W . Then B^c is $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -closed set in W . Thus $\xi^{-1}(B^c)$ is $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -closed set in U and $\xi^{-1}(B^c) = [\xi^{-1}(B)]^c$ which implies that $\xi^{-1}(B)$ is $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -open set in U . Hence $\xi: U \rightarrow W$ is $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -irresolute.

Theorem 4.3. Every $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -irresolute mapping is $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -continuous.

Proof. Let $(U, \Upsilon_{\text{NN}}(S))$ and $(W, \Gamma_{\text{NN}}(T))$ be two $N_{\text{eut}}N_{\text{ano}}$ -Top-Spaces and $\xi: U \rightarrow W$ be a mapping. Let V be a $N_{\text{eut}}N_{\text{ano}}$ -open set in W . Since every $N_{\text{eut}}N_{\text{ano}}$ -open set is $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -open, V is $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -open. Since ξ is $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -irresolute, $\xi^{-1}(V)$ is $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -open in U . Therefore ξ is $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -continuous.

Theorem 4.4. Let $(U, \Upsilon_{\text{NN}}(S))$ and $(W, \Gamma_{\text{NN}}(T))$ be two $N_{\text{eut}}N_{\text{ano}}$ -Top-Spaces and $\xi: U \rightarrow W$ be a mapping. Then ξ is a $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -irresolute mapping if and only if $\xi(N_{\text{eut}}N_{\text{ano}}rg^{**}b-Cl(A)) \subseteq N_{\text{eut}}N_{\text{ano}}rg^{**}b-Cl(\xi(A))$ for every $N_{\text{eut}}N_{\text{ano}}$ -set A in U .

Proof. Let A be a $N_{\text{eut}}N_{\text{ano}}$ -set in U and ξ be a $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -irresolute mapping. Then evidently $\xi(A) \subseteq N_{\text{eut}}N_{\text{ano}}rg^{**}b-Cl[\xi(A)]$. Then we have $A \subseteq \xi^{-1}[\xi(A)] \subseteq \xi^{-1}[N_{\text{eut}}N_{\text{ano}}rg^{**}b-Cl(\xi(A))]$ and hence $N_{\text{eut}}N_{\text{ano}}rg^{**}b-Cl(A) \subseteq N_{\text{eut}}N_{\text{ano}}rg^{**}b-Cl[\xi^{-1}(N_{\text{eut}}N_{\text{ano}}rg^{**}b-Cl(\xi(A)))]$. Since ξ is a $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -irresolute mapping and $N_{\text{eut}}N_{\text{ano}}rg^{**}b-Cl[\xi(A)]$ is a $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -closed set. Therefore $N_{\text{eut}}N_{\text{ano}}rg^{**}b-Cl[\xi^{-1}(N_{\text{eut}}N_{\text{ano}}rg^{**}b-Cl(\xi(A)))] = \xi^{-1}[N_{\text{eut}}N_{\text{ano}}rg^{**}b-Cl(\xi(A))]$. Thus $\xi[N_{\text{eut}}N_{\text{ano}}rg^{**}b-Cl(A)] \subseteq N_{\text{eut}}N_{\text{ano}}rg^{**}b-Cl[\xi(A)]$. Conversely, let $\xi[N_{\text{eut}}N_{\text{ano}}rg^{**}b-Cl(A)] \subseteq N_{\text{eut}}N_{\text{ano}}rg^{**}b-Cl[\xi(A)]$, for each $N_{\text{eut}}N_{\text{ano}}$ -set A in U . Let F be a $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -closed set in W . Then $N_{\text{eut}}N_{\text{ano}}rg^{**}b-Cl(F) = F$. By assumption, $\xi[N_{\text{eut}}N_{\text{ano}}rg^{**}b-Cl(\xi^{-1}(F))] \subseteq N_{\text{eut}}N_{\text{ano}}rg^{**}b-Cl[\xi(\xi^{-1}(F))] \subseteq N_{\text{eut}}N_{\text{ano}}rg^{**}b-Cl(F) = F$ and then this implies that $N_{\text{eut}}N_{\text{ano}}rg^{**}b-Cl[\xi^{-1}(F)] \subseteq \xi^{-1}(F)$. Since $\xi^{-1}(F) \subseteq N_{\text{eut}}N_{\text{ano}}rg^{**}b-Cl[\xi^{-1}(F)]$. Thus we have $N_{\text{eut}}N_{\text{ano}}rg^{**}b-Cl[\xi^{-1}(F)] = \xi^{-1}(F)$. This shows that $\xi^{-1}(F)$ is a $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -closed set in U . Thus, by Theorem 4.3, ξ is a $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -irresolute mapping.

Theorem 4.5. Let $(U, \Upsilon_{\text{NN}}(S))$ and $(W, \Gamma_{\text{NN}}(T))$ be two $N_{\text{eut}}N_{\text{ano}}$ -Top-Spaces and $\xi: U \rightarrow W$ be a mapping. Then ξ is a $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -irresolute mapping if and only if $N_{\text{eut}}N_{\text{ano}}rg^{**}b-Cl[\xi^{-1}(B)] \subseteq \xi^{-1}[N_{\text{eut}}N_{\text{ano}}rg^{**}b-Cl(B)]$ for each $N_{\text{eut}}N_{\text{ano}}$ -set B in W .

Proof. Let $\xi: U \rightarrow W$ be a $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -irresolute mapping. Let B be any $N_{\text{eut}}N_{\text{ano}}$ -set set in W . Since $B \subseteq N_{\text{eut}}N_{\text{ano}}rg^{**}b-Cl(B)$ and therefore we get $\xi^{-1}(B) \subseteq \xi^{-1}[N_{\text{eut}}N_{\text{ano}}rg^{**}b-Cl(B)]$. Then we obtain $N_{\text{eut}}N_{\text{ano}}rg^{**}b-Cl[\xi^{-1}(B)] \subseteq N_{\text{eut}}N_{\text{ano}}rg^{**}b-Cl[\xi^{-1}(N_{\text{eut}}N_{\text{ano}}rg^{**}b-Cl(B))]$. Since $N_{\text{eut}}N_{\text{ano}}rg^{**}b-Cl(B)$ is $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -closed set in W and ξ is a $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -irresolute mapping. So by Theorem 4.3, $\xi^{-1}[N_{\text{eut}}N_{\text{ano}}rg^{**}b-Cl(B)]$ is a $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -closed set in U . Therefore, $N_{\text{eut}}N_{\text{ano}}rg^{**}b-Cl[\xi^{-1}(N_{\text{eut}}N_{\text{ano}}rg^{**}b-Cl(B))]$ is $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -closed set in U . Hence, we have $N_{\text{eut}}N_{\text{ano}}rg^{**}b-Cl[\xi^{-1}(B)] \subseteq \xi^{-1}[N_{\text{eut}}N_{\text{ano}}rg^{**}b-Cl(B)]$. Conversely, let $N_{\text{eut}}N_{\text{ano}}rg^{**}b-Cl[\xi^{-1}(B)] \subseteq \xi^{-1}[N_{\text{eut}}N_{\text{ano}}rg^{**}b-Cl(B)]$ for all $N_{\text{eut}}N_{\text{ano}}$ -sets B in W . Let F be a $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -closed set in W . By assumption, $N_{\text{eut}}N_{\text{ano}}rg^{**}b-Cl[\xi^{-1}(F)] \subseteq \xi^{-1}[N_{\text{eut}}N_{\text{ano}}rg^{**}b-Cl(F)] = \xi^{-1}(F)$. This implies that $\xi^{-1}(F)$ is a $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -closed set in U . Thus by Theorem 4.3, ξ is a $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -irresolute mapping.

Theorem 4.6. Let $(U, \Upsilon_{\text{NN}}(S))$ and $(W, \Gamma_{\text{NN}}(T))$ be two $N_{\text{eut}}N_{\text{ano}}$ -Top-Spaces and $\xi: U \rightarrow W$ be a bijective mapping. Then ξ is $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -irresolute if and only if $N_{\text{eut}}N_{\text{ano}}rg^{**}b-Int[\xi(A)] \subseteq \xi[N_{\text{eut}}N_{\text{ano}}rg^{**}b-Int(A)]$ for every $N_{\text{eut}}N_{\text{ano}}$ -set A in U .

Proof. Let A be any $N_{\text{eut}}N_{\text{ano}}$ -set in U and ξ be a bijective and $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -irresolute mapping. Let $\xi(A) = B$. Since $N_{\text{eut}}N_{\text{ano}}rg^{**}b-Int(B) \subseteq B$ and hence we obtain $\xi^{-1}[N_{\text{eut}}N_{\text{ano}}rg^{**}b-Int(B)] \subseteq \xi^{-1}(B)$. Since ξ is an injective mapping, so $\xi^{-1}(B) = A$. Thus $\xi^{-1}[N_{\text{eut}}N_{\text{ano}}rg^{**}b-Int(B)] \subseteq A$. Then this implies that $N_{\text{eut}}N_{\text{ano}}rg^{**}b-Int[\xi^{-1}(N_{\text{eut}}N_{\text{ano}}rg^{**}b-Int(B))]$ $\subseteq N_{\text{eut}}N_{\text{ano}}rg^{**}b-Int(A)$. Since ξ is $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -irresolute, $\xi^{-1}[N_{\text{eut}}N_{\text{ano}}rg^{**}b-Int(B)]$ is $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -open set in U and therefore $\xi^{-1}[N_{\text{eut}}N_{\text{ano}}rg^{**}b-Int(B)] \subseteq N_{\text{eut}}N_{\text{ano}}rg^{**}b-Int(A)$. Hence $\xi[\xi^{-1}(N_{\text{eut}}N_{\text{ano}}rg^{**}b-Int(B))]$ $\subseteq \xi[N_{\text{eut}}N_{\text{ano}}rg^{**}b-Int(A)]$. Thus $N_{\text{eut}}N_{\text{ano}}rg^{**}b-Int[\xi(A)] \subseteq \xi[N_{\text{eut}}N_{\text{ano}}rg^{**}b-Int(A)]$.
Conversely, let $N_{\text{eut}}N_{\text{ano}}rg^{**}b-Int[\xi(A)] \subseteq \xi[N_{\text{eut}}N_{\text{ano}}rg^{**}b-Int(A)]$ for every $N_{\text{eut}}N_{\text{ano}}$ -set A in U . Let V be a $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -open set in W . Since ξ is surjective and therefore, by hypothesis, $V = N_{\text{eut}}N_{\text{ano}}rg^{**}b-Int(V) = N_{\text{eut}}N_{\text{ano}}rg^{**}b-Int[\xi(\xi^{-1}(V))] \subseteq \xi[N_{\text{eut}}N_{\text{ano}}rg^{**}b-Int(\xi^{-1}(V))]$. It follows that $\xi^{-1}(V) \subseteq N_{\text{eut}}N_{\text{ano}}rg^{**}b-Int[\xi^{-1}(V)]$. Therefore $\xi^{-1}(V)$ is $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -open set in U . Hence ξ is a $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -irresolute mapping.

Theorem 4.7. Let $(U, \Upsilon_{\text{NN}}(S))$ and $(W, \Gamma_{\text{NN}}(T))$ be two $N_{\text{eut}}N_{\text{ano}}$ -Top-Spaces and $\xi: U \rightarrow W$ be a mapping.. Then ξ is a $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -irresolute mapping if and only if $\xi^{-1}[N_{\text{eut}}N_{\text{ano}}rg^{**}b-Int(B)] \subseteq N_{\text{eut}}N_{\text{ano}}rg^{**}b-Int[\xi^{-1}(B)]$ for every $N_{\text{eut}}N_{\text{ano}}$ -set B in W .

Proof. Let B be any $N_{\text{eut}}N_{\text{ano}}$ -set in W and ξ be a $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -irresolute mapping. Then $N_{\text{eut}}N_{\text{ano}}rg^{**}b-Int(B) \subseteq B$ implies $\xi^{-1}[N_{\text{eut}}N_{\text{ano}}rg^{**}b-Int(B)] \subseteq \xi^{-1}(B)$. Hence, $N_{\text{eut}}N_{\text{ano}}rg^{**}b-Int[\xi^{-1}(N_{\text{eut}}N_{\text{ano}}rg^{**}b-Int(B))]$ $\subseteq N_{\text{eut}}N_{\text{ano}}rg^{**}b-Int[\xi^{-1}(B)]$. Since $N_{\text{eut}}N_{\text{ano}}rg^{**}b-Int(B)$ is $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -open set in W and ξ is $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -irresolute, $\xi^{-1}[N_{\text{eut}}N_{\text{ano}}rg^{**}b-Int(B)]$ is $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -open set in U . Thus $N_{\text{eut}}N_{\text{ano}}rg^{**}b-Int[\xi^{-1}(N_{\text{eut}}N_{\text{ano}}rg^{**}b-Int(B))]$ $= \xi^{-1}[N_{\text{eut}}N_{\text{ano}}rg^{**}b-Int(B)]$. Then we obtain $\xi^{-1}[N_{\text{eut}}N_{\text{ano}}rg^{**}b-Int(B)] \subseteq N_{\text{eut}}N_{\text{ano}}rg^{**}b-Int[\xi^{-1}(B)]$.
Conversely, let $\xi^{-1}[N_{\text{eut}}N_{\text{ano}}rg^{**}b-Int(B)] \subseteq N_{\text{eut}}N_{\text{ano}}rg^{**}b-Int[\xi^{-1}(B)]$ for every $N_{\text{eut}}N_{\text{ano}}$ -set B in W . Let G be any $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -open set in W . Then by assumption, $\xi^{-1}(G) = \xi^{-1}[N_{\text{eut}}N_{\text{ano}}rg^{**}b-Int(G)] \subseteq N_{\text{eut}}N_{\text{ano}}rg^{**}b-Int[\xi^{-1}(G)]$ and therefore $\xi^{-1}(G) \subseteq N_{\text{eut}}N_{\text{ano}}rg^{**}b-Int[\xi^{-1}(G)]$. This implies that $\xi^{-1}(G)$ is $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -open set in U . Hence ξ is a $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -irresolute mapping.

Theorem 4.8. Let $(U, \Upsilon_{\text{NN}}(S))$ and $(W, \Gamma_{\text{NN}}(T))$ be two $N_{\text{eut}}N_{\text{ano}}$ -Top-Spaces and $\xi: U \rightarrow W$ be a bijective mapping. Then ξ is a $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -irresolute mapping. Then prove that $\xi[N_{\text{eut}}N_{\text{ano}}rg^{**}b-Fr(A)] \subseteq N_{\text{eut}}N_{\text{ano}}rg^{**}b-Fr[\xi(A)]$ for every $N_{\text{eut}}N_{\text{ano}}$ -set A in U .

Proof. Let ξ be a bijective and $N_{eut}N_{ano}rg^{**}b$ -irresolute mapping. Let A be a $N_{eut}N_{ano}$ -set in U . By definition, $N_{eut}N_{ano}rg^{**}b-Fr(A) = N_{eut}N_{ano}rg^{**}b-Cl(A) \cap N_{eut}N_{ano}rg^{**}b-Cl(A^c)$. By Theorem 4.6, $N_{eut}N_{ano}rg^{**}b-Int[\xi(A)] \subseteq \xi[N_{eut}N_{ano}rg^{**}b-Int(A)]$ and from Theorem 4.4, $\xi[N_{eut}N_{ano}rg^{**}b-Cl(A)] \subseteq N_{eut}N_{ano}rg^{**}b-Cl[\xi(A)]$. So $\xi[N_{eut}N_{ano}rg^{**}b-Fr(A)] = \xi[N_{eut}N_{ano}rg^{**}b-Cl(A)] \cap \xi[N_{eut}N_{ano}rg^{**}b-Cl(A^c)] \subseteq N_{eut}N_{ano}rg^{**}b-Cl[\xi(A)] \cap N_{eut}N_{ano}rg^{**}b-Cl[\xi(A)^c] = N_{eut}N_{ano}rg^{**}b-Fr[\xi(A)]$.

Theorem 4.9. Let $(U, \Upsilon_{NN}(S))$ and $(W, \Gamma_{NN}(T))$ be two $N_{eut}N_{ano}$ -Top-Spaces and $\xi: U \rightarrow W$ be a bijective $N_{eut}N_{ano}rg^{**}b$ -irresolute mapping. Then we have $N_{eut}N_{ano}rg^{**}b-Fr[\xi^{-1}(B)] \subseteq \xi^{-1}[N_{eut}N_{ano}rg^{**}b-Fr(B)]$ for every $N_{eut}N_{ano}$ -set B in W .

Proof. Let ξ be a bijective and $N_{eut}N_{ano}rg^{**}b$ -irresolute mapping. Let B be a $N_{eut}N_{ano}$ -set in W . By Theorem 4.5, we have $N_{eut}N_{ano}rg^{**}b-Cl[\xi^{-1}(B)] \subseteq \xi^{-1}[N_{eut}N_{ano}rg^{**}b-Cl(B)]$. Now $\xi^{-1}[N_{eut}N_{ano}rg^{**}b-Fr(B)] = \xi^{-1}[(N_{eut}N_{ano}rg^{**}b-Cl(B)) \cap N_{eut}N_{ano}rg^{**}b-Cl(B^c)] = \xi^{-1}[N_{eut}N_{ano}rg^{**}b-Cl(B)] \cap \xi^{-1}[N_{eut}N_{ano}rg^{**}b-Cl(B^c)] \supseteq N_{eut}N_{ano}rg^{**}b-Cl[\xi^{-1}(B)] \cap N_{eut}N_{ano}rg^{**}b-Cl[\xi^{-1}(B^c)] = N_{eut}N_{ano}rg^{**}b-Cl[\xi^{-1}(B)] \cap N_{eut}N_{ano}rg^{**}b-Cl[(\xi^{-1}(B))^c] = N_{eut}N_{ano}rg^{**}b-Fr[\xi^{-1}(B)]$. Therefore we obtain $N_{eut}N_{ano}rg^{**}b-Fr[\xi^{-1}(B)] \subseteq \xi^{-1}[N_{eut}N_{ano}rg^{**}b-Fr(B)]$.

Theorem 4.10. If $\xi: (U, \Upsilon_{NN}(S)) \rightarrow (W, \Gamma_{NN}(S^*))$ and $\eta: (W, \Gamma_{NN}(S^*)) \rightarrow (Z, \Psi_{NN}(S^{**}))$ are $N_{eut}N_{ano}rg^{**}b$ -irresolute, then their composition function $\eta \circ \xi: (U, \Upsilon_{NN}(S)) \rightarrow (Z, \Psi_{NN}(S^{**}))$ is also $N_{eut}N_{ano}rg^{**}b$ -irresolute.

Proof. Let V be a $N_{eut}N_{ano}rg^{**}b$ -open set in Z . Since η is a $N_{eut}N_{ano}rg^{**}b$ -irresolute mapping, $\eta^{-1}(V)$ is $N_{eut}N_{ano}rg^{**}b$ -open in W . Since ξ is a $N_{eut}N_{ano}rg^{**}b$ -irresolute mapping, $\xi^{-1}[\eta^{-1}(V)] = (\eta \circ \xi)^{-1}(V)$ is $N_{eut}N_{ano}rg^{**}b$ -open in U . Therefore $\eta \circ \xi$ is $N_{eut}N_{ano}rg^{**}b$ -irresolute.

Theorem 4.11. If $\xi: (U, \Upsilon_{NN}(S)) \rightarrow (W, \Gamma_{NN}(S^*))$ is $N_{eut}N_{ano}rg^{**}b$ -irresolute and $\eta: (W, \Gamma_{NN}(S^*)) \rightarrow (Z, \Psi_{NN}(S^{**}))$ is $N_{eut}N_{ano}rg^{**}b$ -continuous, then their composition function $\eta \circ \xi: (U, \Upsilon_{NN}(S)) \rightarrow (Z, \Psi_{NN}(S^{**}))$ is also a $N_{eut}N_{ano}rg^{**}b$ -continuous function.

Proof. Let V be a $N_{eut}N_{ano}$ -open set in Z . Since η is a $N_{eut}N_{ano}rg^{**}b$ -continuous mapping, $\eta^{-1}(V)$ is $N_{eut}N_{ano}rg^{**}b$ -open set in W . Since ξ is a $N_{eut}N_{ano}rg^{**}b$ -irresolute mapping, $\xi^{-1}[\eta^{-1}(V)] = (\eta \circ \xi)^{-1}(V)$ is $N_{eut}N_{ano}rg^{**}b$ -open in U . Therefore $\eta \circ \xi$ is $N_{eut}N_{ano}rg^{**}b$ -continuous.

5. Neutrosophic Nano Regular Generalized Star Star B-Closed Maps and Neutrosophic Nano Regular Generalized Star Star B-Open Maps

In this section, we introduce neutrosophic nano $rg^{**}b$ -closed ($N_{eut}N_{ano}rg^{**}b$ -closed) mappings and neutrosophic nano $rg^{**}b$ -open ($N_{eut}N_{ano}rg^{**}b$ -open) mappings in $N_{eut}N_{ano}$ -Top-Spaces and obtain certain characterizations of these classes of mappings.

Definition 5.1. Let $(U, \Upsilon_{NN}(S))$ and $(W, \Gamma_{NN}(S^*))$ be two $N_{eut}N_{ano}$ -Top-Spaces. A function $\xi: (U, \Upsilon_{NN}(S)) \rightarrow (W, \Gamma_{NN}(S^*))$ is said to be $N_{eut}N_{ano}rg^{**}b$ -closed if the image of each $N_{eut}N_{ano}$ -closed set in U is $N_{eut}N_{ano}rg^{**}b$ -closed in W .

Definition 5.2. Let $(U, \Upsilon_{NN}(S))$ and $(W, \Gamma_{NN}(S^*))$ be two $N_{eut}N_{ano}$ -Top-Spaces. A function $\xi: (U, \Upsilon_{NN}(S)) \rightarrow (W, \Gamma_{NN}(S^*))$ is said to be $N_{eut}N_{ano}rg^{**}b$ -open if the image of each $N_{eut}N_{ano}$ -open set in U is $N_{eut}N_{ano}rg^{**}b$ -open in W .

Theorem 5.3. Prove that a function $\xi: (U, \Upsilon_{NN}(S)) \rightarrow (W, \Gamma_{NN}(S^*))$ is $N_{eut}N_{ano}rg^{**}b$ -closed if and only if $N_{eut}N_{ano}rg^{**}b-Cl[\xi(A)] \subseteq \xi[N_{eut}N_{ano}-Cl(A)]$ for every $N_{eut}N_{ano}$ -set A of U .

Proof. Suppose $\xi: (U, \Upsilon_{NN}(S)) \rightarrow (W, \Gamma_{NN}(S^*))$ is a $N_{eut}N_{ano}rg^{**}b$ -closed function and A is any $N_{eut}N_{ano}$ -set in U . Then $N_{eut}N_{ano}-Cl(A)$ is a $N_{eut}N_{ano}$ -closed set in U . Since ξ is $N_{eut}N_{ano}rg^{**}b$ -closed, $\xi[N_{eut}N_{ano}-Cl(A)]$ is a $N_{eut}N_{ano}rg^{**}b$ -closed set in W . Thus $N_{eut}N_{ano}rg^{**}b-Cl[\xi(N_{eut}N_{ano}-Cl(A))] = \xi[N_{eut}N_{ano}-Cl(A)]$. Therefore we obtain $N_{eut}N_{ano}rg^{**}b-Cl[\xi(A)] \subseteq N_{eut}N_{ano}rg^{**}b-Cl[\xi(N_{eut}N_{ano}-Cl(A))] = \xi(N_{eut}N_{ano}-Cl(A))$. Hence $N_{eut}N_{ano}rg^{**}b-Cl[\xi(A)] \subseteq \xi(N_{eut}N_{ano}-Cl(A))$.

Conversely, let A be a $N_{eut}N_{ano}$ -closed set in U . Then $N_{eut}N_{ano}-Cl(A) = A$ and so $\xi(A) = \xi[N_{eut}N_{ano}-Cl(A)]$. By our assumption $N_{eut}N_{ano}rg^{**}b-Cl[\xi(A)] \subseteq \xi(A)$. But $\xi(A) \subseteq N_{eut}N_{ano}rg^{**}b-Cl[\xi(A)]$. Hence $N_{eut}N_{ano}rg^{**}b-Cl[\xi(A)] = \xi(A)$ and therefore $\xi(A)$ is $N_{eut}N_{ano}rg^{**}b$ -closed set in W . Thus ξ is a $N_{eut}N_{ano}rg^{**}b$ -closed mapping.

Theorem 5.4. A mapping $\xi: (U, \Upsilon_{NN}(S)) \rightarrow (W, \Gamma_{NN}(S^*))$ is $N_{eut}N_{ano}rg^{**}b$ -closed if and only if for each $N_{eut}N_{ano}$ -set H of W and for each $N_{eut}N_{ano}$ -open set G of U containing $\xi^{-1}(H)$ there exists a $N_{eut}N_{ano}rg^{**}b$ -open set V of W such that $H \subseteq V$ and $\xi^{-1}(V) \subseteq G$.

Proof. Suppose ξ is a $N_{eut}N_{ano}rg^{**}b$ -closed mapping. Let H be any $N_{eut}N_{ano}$ -set in W and G be a $N_{eut}N_{ano}$ -open set of U such that $\xi^{-1}(H) \subseteq G$. Then $V = [\xi(G^c)]^c$ is $N_{eut}N_{ano}rg^{**}b$ -open in W such that $\xi^{-1}(V) \subseteq G$.

Conversely, let H be a $N_{eut}N_{ano}$ -closed of W . Then $\xi^{-1}[(\xi(H))^c] \subseteq H^c$ and H^c is $N_{eut}N_{ano}$ -open in U . By assumption, there exists a $N_{eut}N_{ano}rg^{**}b$ -open set V of W such that $[\xi(H)]^c \subseteq V$ and $\xi^{-1}(V) \subseteq H^c$ and so $H \subseteq [\xi^{-1}(V)]^c$. Hence $V^c \subseteq \xi(H) \subseteq \xi([\xi^{-1}(V)]^c) \subseteq V^c$, which implies $\xi(H) = V^c$.

Since V^c is $N_{eut}N_{ano}rg^{**}b$ -closed, $\xi(H)$ is $N_{eut}N_{ano}rg^{**}b$ -closed and ξ is $N_{eut}N_{ano}rg^{**}b$ -closed mapping.

Theorem 5.5. Let $\xi : (U, \Upsilon_{\text{NN}}(S)) \rightarrow (W, \Gamma_{\text{NN}}(S^*))$ be a $N_{\text{eut}}N_{\text{ano}}$ -closed mapping and $\eta : (W, \Gamma_{\text{NN}}(S^*)) \rightarrow (Z, \Psi_{\text{NN}}(S^{**}))$ be a $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -closed mapping. Then their composition $\eta \circ \xi : (U, \Upsilon_{\text{NN}}(S)) \rightarrow (Z, \Psi_{\text{NN}}(S^{**}))$ is a $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -closed mapping.

Proof. Let F be a $N_{\text{eut}}N_{\text{ano}}$ -closed set in U . Since ξ is $N_{\text{eut}}N_{\text{ano}}$ -closed, $\xi(F)$ is $N_{\text{eut}}N_{\text{ano}}$ -closed in W . Since η is $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -closed, $\eta[\xi(F)] = (\eta \circ \xi)(F)$ is $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -closed in Z . Hence $\eta \circ \xi$ is a $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -closed mapping.

Theorem 5.6. Let $\xi : (U, \Upsilon_{\text{NN}}(S)) \rightarrow (W, \Gamma_{\text{NN}}(S^*))$ and $\eta : (W, \Gamma_{\text{NN}}(S^*)) \rightarrow (Z, \Psi_{\text{NN}}(S^{**}))$ be two mappings such that their composition $\eta \circ \xi : (U, \Upsilon_{\text{NN}}(S)) \rightarrow (Z, \Psi_{\text{NN}}(S^{**}))$ is $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -closed. Then the following statements are true.

- (i) If ξ is $N_{\text{eut}}N_{\text{ano}}$ -continuous and surjective, then η is $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -closed.
- (ii) If η is $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -irresolute and injective, then ξ is $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -closed.

Proof. (i) Let A be a $N_{\text{eut}}N_{\text{ano}}$ -closed set of W . Since ξ is $N_{\text{eut}}N_{\text{ano}}$ -continuous, $\xi^{-1}(A)$ is $N_{\text{eut}}N_{\text{ano}}$ -closed in U . Since $\eta \circ \xi$ is $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -closed, $(\eta \circ \xi)(\xi^{-1}(A))$ is $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -closed in Z . Since ξ is surjective, $(\eta \circ \xi)(\xi^{-1}(A)) = \eta(A)$ is $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -closed in Z . Hence η is $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -closed.

(ii) Let B be any $N_{\text{eut}}N_{\text{ano}}$ -closed set of U . Since $\eta \circ \xi$ is $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -closed, $(\eta \circ \xi)(B)$ is $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -closed in Z . Since η is $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -irresolute, $\eta^{-1}(\eta \circ \xi(B))$ is $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -closed in W . Since η is injective, $\eta^{-1}(\eta \circ \xi(B)) = \eta^{-1}(\eta(\xi(B))) = \xi(B)$ is $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -closed in W . Hence ξ is $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -closed.

Theorem 5.7. A function $\xi : (U, \Upsilon_{\text{NN}}(S)) \rightarrow (W, \Gamma_{\text{NN}}(T))$ is $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -open if and only if $\xi[N_{\text{eut}}\text{Int}(A)] \subseteq N_{\text{eut}}N_{\text{ano}}rg^{**}b - \text{Int}[\xi(A)]$, for every $N_{\text{eut}}N_{\text{ano}}$ -set A of U .

Proof. Suppose $\xi : (U, \Upsilon_{\text{NN}}(S)) \rightarrow (W, \Gamma_{\text{NN}}(T))$ is a $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -open function and A is any $N_{\text{eut}}N_{\text{ano}}$ -set in U . Then $N_{\text{eut}}N_{\text{ano}} - \text{Int}(A)$ is a $N_{\text{eut}}N_{\text{ano}}$ -open set in U . Since ξ is $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -open, $\xi[N_{\text{eut}}N_{\text{ano}} - \text{Int}(A)]$ is a $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -open set. Since $N_{\text{eut}}N_{\text{ano}}rg^{**}b - \text{Int}[\xi(N_{\text{eut}}N_{\text{ano}} - \text{Int}(A))] \subseteq N_{\text{eut}}N_{\text{ano}}rg^{**}b - \text{Int}[\xi(A)]$, $\xi[N_{\text{eut}}N_{\text{ano}} - \text{Int}(A)] \subseteq N_{\text{eut}}N_{\text{ano}}rg^{**}b - \text{Int}[\xi(A)]$.

Conversely, $\xi[N_{\text{eut}}\text{Int}(A)] \subseteq N_{\text{eut}}N_{\text{ano}}rg^{**}b - \text{Int}[\xi(A)]$ for every $N_{\text{eut}}N_{\text{ano}}$ -set A in U . Let U be a $N_{\text{eut}}N_{\text{ano}}$ -open set in U . Then $N_{\text{eut}}N_{\text{ano}} - \text{Int}(U) = U$ and by hypothesis, $\xi(U) \subseteq N_{\text{eut}}N_{\text{ano}}rg^{**}b - \text{Int}[\xi(U)]$. But $N_{\text{eut}}N_{\text{ano}}rg^{**}b - \text{Int}[\xi(U)] \subseteq \xi(U)$. Therefore, $\xi(U) = N_{\text{eut}}N_{\text{ano}}rg^{**}b - \text{Int}[\xi(U)]$. Then $\xi(U)$ is $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -open. Hence ξ is a $N_{\text{eut}}N_{\text{ano}}rg^{**}b$ -open mapping.

Theorem 5.8. Let $\xi: (U, \Upsilon_{\text{NN}}(S)) \rightarrow (W, \Gamma_{\text{NN}}(S^*))$ be a $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -open function. If for each $x_{(r,s,t)} \in U$ and for each $N_{\text{cut}}N_{\text{ano}}$ -neighbourhood G of $x_{(r,s,t)}$ in U , there exists a $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -neighborhood H of $\xi(x_{(r,s,t)})$ in W such that $H \subseteq \xi(G)$.

Proof. Let $\xi: (U, \Upsilon_{\text{NN}}(S)) \rightarrow (W, \Gamma_{\text{NN}}(S^*))$ be a $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -open function. Let $x_{(r,s,t)} \in U$ and G be any arbitrary $N_{\text{cut}}N_{\text{ano}}$ -neighbourhood of $x_{(r,s,t)}$ in U . Then there exists a $N_{\text{cut}}N_{\text{ano}}$ -open set P such that $x_{(r,s,t)} \in P \subseteq G$. By Theorem 5.7, $\xi(P) = \xi[N_{\text{cut}}N_{\text{ano}}\text{-Int}(P)] \subseteq N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}\text{-Int}[\xi(P)]$. But, $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}\text{-Int}[\xi(P)] \subseteq \xi(P)$. Therefore, $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}\text{-Int}[\xi(P)] = \xi(P)$ and hence $\xi(P)$ is $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -open in W . Since $x_{(r,s,t)} \in P \subseteq G$, $\xi(x_{(r,s,t)}) \in \xi(P) \subseteq \xi(G)$ and so the result follows by taking $H = \xi(P)$.

Theorem 5.9. For any bijective mapping $\xi: (U, \Upsilon_{\text{NN}}(S)) \rightarrow (W, \Gamma_{\text{NN}}(S^*))$ the following statements are equivalent:

- (i) $\xi^{-1}: (W, \Gamma_{\text{NN}}(S^*)) \rightarrow (U, \Upsilon_{\text{NN}}(S))$ is $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -continuous.
- (ii) ξ is $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -open.
- (iii) ξ is $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -closed.

Proof. (i) $\Rightarrow$ (ii): Let G be a $N_{\text{cut}}N_{\text{ano}}$ -set set in U . By assumption, $(\xi^{-1})^{-1}(G) = \xi(G)$ is $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -open in W and so ξ is $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -open.

(ii) $\Rightarrow$ (iii): Let F be a $N_{\text{cut}}N_{\text{ano}}$ -closed set of U . Then F^c is a $N_{\text{cut}}N_{\text{ano}}$ -open set in U . By assumption $\xi(F^c)$ is $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -open in W . But $\xi(F^c) = [\xi(F)]^c$. Therefore $\xi(F)$ is $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -closed set in W . Hence, ξ is $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -closed.

(iii) $\Rightarrow$ (i): Let F be a $N_{\text{cut}}N_{\text{ano}}$ -closed set of U . By assumption, $\xi(F)$ is $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -closed set in W . But $\xi(F) = (\xi^{-1})^{-1}(F)$ and therefore by Theorem 3.4, $\xi^{-1}: W \rightarrow U$ is $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -continuous.

6. Strongly Neutrosophic Nano Regular Generalized Star Star B-Continuous Maps and Perfectly Neutrosophic Nano Regular Generalized Star Star B-Continuous Maps

In this section, we introduce and study the concepts of strongly $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -continuous and perfectly $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -continuous mappings in $N_{\text{cut}}N_{\text{ano}}$ -Top-Spaces.

Definition 6.1. A function $\xi: (U, \Upsilon_{\text{NN}}(S)) \rightarrow (W, \Gamma_{\text{NN}}(S^*))$ is called strongly $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -continuous if the inverse image of every $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -open set in W is $N_{\text{cut}}N_{\text{ano}}$ -open in U .

Definition 6.2. A function $\xi: (U, \Upsilon_{\text{NN}}(S)) \rightarrow (W, \Gamma_{\text{NN}}(S^*))$ is called perfectly $N_{\text{cut}}N_{\text{ano}}$ -continuous if the inverse image of every $N_{\text{cut}}N_{\text{ano}}$ -open set in W is $N_{\text{cut}}N_{\text{ano}}$ -clopen in U .

Definition 6.3. A function $\xi: (U, \Upsilon_{\text{NN}}(S)) \rightarrow (W, \Gamma_{\text{NN}}(S^*))$ is called perfectly $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -continuous if the inverse image of every $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -open set in W is $N_{\text{cut}}N_{\text{ano}}$ -clopen in U .

Theorem 6.4. Let $\xi: (U, \Upsilon_{\text{NN}}(S)) \rightarrow (W, \Gamma_{\text{NN}}(S^*))$ be a mapping. Then the following statements are true:

- (i) If ξ is perfectly $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -continuous, then ξ is perfectly $N_{\text{cut}}N_{\text{ano}}$ -continuous.
- (ii) If ξ is strongly $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -continuous, then ξ is $N_{\text{cut}}N_{\text{ano}}$ -continuous.

Proof. (i) Let $\xi: (U, \Upsilon_{\text{NN}}(S)) \rightarrow (W, \Gamma_{\text{NN}}(S^*))$ be perfectly $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -continuous. Let V be a $N_{\text{cut}}N_{\text{ano}}$ -open set in W . Then V is $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -open set in W . Since ξ is perfectly $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -continuous, $\xi^{-1}(V)$ is $N_{\text{cut}}N_{\text{ano}}$ -clopen in U . Hence ξ is perfectly $N_{\text{cut}}N_{\text{ano}}$ -continuous.

(ii) Let $\xi: U \rightarrow W$ be strongly $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -continuous. Let G be $N_{\text{cut}}N_{\text{ano}}$ -open set in W . Then G is $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -open set in W . Since ξ is strongly $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -continuous, $\xi^{-1}(G)$ is $N_{\text{cut}}N_{\text{ano}}$ -open in U . Therefore ξ is $N_{\text{cut}}N_{\text{ano}}$ -continuous.

Theorem 6.5. Let $\xi: (U, \Upsilon_{\text{NN}}(S)) \rightarrow (W, \Gamma_{\text{NN}}(S^*))$ be strongly $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -continuous and A be a $N_{\text{cut}}N_{\text{ano}}$ -open set in W . Then the restriction map, $\xi_A: A \rightarrow W$ is strongly $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -continuous.

Proof. Let V be any $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -open set in W . Since ξ is strongly $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -continuous, $\xi^{-1}(V)$ is $N_{\text{cut}}N_{\text{ano}}$ -open in U . But $\xi_A^{-1}(V) = A \cap \xi^{-1}(V)$. Since A and $\xi^{-1}(V)$ are $N_{\text{cut}}N_{\text{ano}}$ -open, $\xi_A^{-1}(V)$ is $N_{\text{cut}}N_{\text{ano}}$ -open in A . Hence ξ_A is strongly $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -continuous.

Theorem 6.5. Every perfectly $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -continuous mapping $\xi: (U, \Upsilon_{\text{NN}}(S)) \rightarrow (W, \Gamma_{\text{NN}}(S^*))$ is strongly $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -continuous.

Proof. Let $\xi: U \rightarrow W$ be perfectly $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -continuous and V be $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -open set in W . Since ξ is perfectly $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -continuous, $\xi^{-1}(V)$ is $N_{\text{cut}}N_{\text{ano}}$ -clopen in U . Thus $\xi^{-1}(V)$ is $N_{\text{cut}}N_{\text{ano}}$ -open in U . Hence ξ is strongly $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -continuous.

Theorem 6.6. If $\xi: (U, \Upsilon_{\text{NN}}(S)) \rightarrow (W, \Gamma_{\text{NN}}(S^*))$ and $\eta: (W, \Gamma_{\text{NN}}(S^*)) \rightarrow (Z, \Psi_{\text{NN}}(S^{**}))$ are strongly $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -continuous, then $\eta \circ \xi: (U, \Upsilon_{\text{NN}}(S)) \rightarrow (Z, \Psi_{\text{NN}}(S^{**}))$ is also strongly $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -continuous.

Proof. Let V be a $N_{\text{cut}}N_{\text{ano}}$ -open set in Z . Since η is a strongly $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -continuous mapping, $\eta^{-1}(V)$ is $N_{\text{cut}}N_{\text{ano}}$ -open in W . Since ξ is a strongly $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -continuous mapping, $\xi^{-1}[\eta^{-1}(V)] = (\eta \circ \xi)^{-1}(V)$ is $N_{\text{cut}}N_{\text{ano}}$ -open in U . Therefore, $\eta \circ \xi$ is strongly $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -continuous.

Theorem 6.7. If $\xi: (U, \Upsilon_{\text{NN}}(S)) \rightarrow (W, \Gamma_{\text{NN}}(S^*))$ and $\eta: (W, \Gamma_{\text{NN}}(S^*)) \rightarrow (Z, \Psi_{\text{NN}}(S^{**}))$ are perfectly $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -continuous mappings, then their composition $\eta \circ \xi: (U, \Upsilon_{\text{NN}}(S)) \rightarrow (Z, \Psi_{\text{NN}}(S^{**}))$ is also perfectly $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -continuous mapping.

Proof. Let V be a $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -open set in Z . Since η is a perfectly $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -continuous mapping, $\eta^{-1}(V)$ is $N_{\text{cut}}N_{\text{ano}}$ -clopen in W . That is $\eta^{-1}(V)$ both $N_{\text{cut}}N_{\text{ano}}$ -open and $N_{\text{cut}}N_{\text{ano}}$ -closed in

U . Then $\eta^{-1}(V)$ is $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -open set in U . Since ξ is a perfectly $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -continuous mapping, $\xi^{-1}[\eta^{-1}(V)] = (gof)^{-1}(V)$ is $N_{\text{cut}}N_{\text{ano}}$ -clopen in U . Therefore $\eta o \xi$ is perfectly $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -continuous.

Theorem 6.8. Let $\xi: (U, \Upsilon_{\text{NN}}(S)) \rightarrow (W, \Gamma_{\text{NN}}(S^*))$ and $\eta: (W, \Gamma_{\text{NN}}(S^*)) \rightarrow (Z, \Psi_{\text{NN}}(S^{**}))$ be mappings. Then the following statements are true.

- (i) If η is strongly $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -continuous and ξ is $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -continuous, then $\eta o \xi$ is $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -irresolute.
- (ii) If η is perfectly $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -continuous and ξ is $N_{\text{cut}}N_{\text{ano}}$ -continuous, then $\eta o \xi$ is strongly $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -continuous.
- (iii) If η is strongly $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -continuous and ξ is perfectly $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -continuous, then $\eta o \xi$ is perfectly $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -continuous.
- (iv) If η is $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -continuous and ξ is strongly $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -continuous, then $\eta o \xi$ is $N_{\text{cut}}N_{\text{ano}}$ -continuous,

Proof. (i) Let V be a $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -open set in Z . Since η is a strongly $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -continuous mapping, $\eta^{-1}(V)$ is $N_{\text{cut}}N_{\text{ano}}$ -open set in W . Since ξ is a $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -continuous mapping, $\xi^{-1}[\eta^{-1}(V)] = (\eta o \xi)^{-1}(V)$ is $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -open set in U . Hence $\eta o \xi$ is $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -irresolute.

(ii) Let V be a $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -open set in Z . Since η is a perfectly $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -continuous mapping, $\eta^{-1}(V)$ is $N_{\text{cut}}N_{\text{ano}}$ -clopen set in W . That is, $\eta^{-1}(V)$ is both $N_{\text{cut}}N_{\text{ano}}$ -open and $N_{\text{cut}}N_{\text{ano}}$ -closed. Since ξ is a $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -continuous mapping, $\xi^{-1}[\eta^{-1}(V)] = (\eta o \xi)^{-1}(V)$ is $N_{\text{cut}}N_{\text{ano}}$ -open in U . Therefore $\eta o \xi$ is strongly $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -continuous.

(iii) Let V be a $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -open set in Z . Since η is a strongly $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -continuous mapping, $\eta^{-1}(V)$ is $N_{\text{cut}}N_{\text{ano}}$ -open set in W . Since every $N_{\text{cut}}N_{\text{ano}}$ -open set is $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -open set. So $\eta^{-1}(V)$ is $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -open set in U . Since ξ is a perfectly $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -continuous mapping, $\xi^{-1}[\eta^{-1}(V)] = (\eta o \xi)^{-1}(V)$ is $N_{\text{cut}}N_{\text{ano}}$ -clopen in U . Hence $\eta o \xi$ is perfectly $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -continuous.

(iv) Let V be a $N_{\text{cut}}N_{\text{ano}}$ -open set in Z . Since η is a $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -continuous mapping, $\eta^{-1}(V)$ is $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -open set in W . Since ξ is a strongly $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -continuous map, $\xi^{-1}[\eta^{-1}(V)] = (\eta o \xi)^{-1}(V)$ is $N_{\text{cut}}N_{\text{ano}}$ -open in U . So $\eta o \xi$ is $N_{\text{cut}}N_{\text{ano}}$ -continuous.

7. Neutrosophic Nano Contra Regular Generalized Star Star B-Continuous Maps and Neutrosophic Nano Contra Regular Generalized Star Star B-Irresolute Maps

In this section, we introduce the concepts of neutrosophic nano contra $N_{\text{cut}}N_{\text{ano}}rg^{**}b$ -continuous ($N_{\text{cut}}N_{\text{ano}}\text{Contra-}rg^{**}b$ -continuous) mappings and neutrosophic nano contra $rg^{**}b$ -irresolute ($N_{\text{cut}}N_{\text{ano}}\text{Contra-}rg^{**}b$ -irresolute) mappings and investigate their fundamental properties and characterizations.

Definition 7.1. A function $\xi: (U, \Upsilon_{\text{NN}}(S)) \rightarrow (W, \Gamma_{\text{NN}}(S^*))$ is said to be $N_{\text{cut}}N_{\text{ano}}\text{Contra}$ -continuous if the inverse image of every $N_{\text{cut}}N_{\text{ano}}$ -open set in W is $N_{\text{cut}}N_{\text{ano}}$ -closed set in U .

Definition 7.2. A function $\xi: (U, \Upsilon_{\text{NN}}(S)) \rightarrow (W, \Gamma_{\text{NN}}(S^*))$ is said to be $N_{\text{cut}}N_{\text{ano}}\text{Contra-rg**b}$ -continuous if the inverse image of every $N_{\text{cut}}N_{\text{ano}}$ -open set in W is $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -closed in U .

Theorem 7.3. Let $\xi: (U, \Upsilon_{\text{NN}}(S)) \rightarrow (W, \Gamma_{\text{NN}}(S^*))$ be a $N_{\text{cut}}N_{\text{ano}}\text{Contra}$ -continuous mapping. Then ξ is $N_{\text{cut}}N_{\text{ano}}\text{Contra-rg**b}$ -continuous.

Proof. Let V be any $N_{\text{cut}}N_{\text{ano}}$ -open set in W . Since ξ is $N_{\text{cut}}N_{\text{ano}}\text{Contra}$ -continuous, $\xi^{-1}(V)$ is $N_{\text{cut}}N_{\text{ano}}$ -closed set in U . As every $N_{\text{cut}}N_{\text{ano}}$ -closed set is $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -closed, we have $\xi^{-1}(V)$ is $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -closed set in U . Therefore ξ is $N_{\text{cut}}N_{\text{ano}}\text{Contra-rg**b}$ -continuous.

Theorem 7.4. Prove that a function $\xi: (U, \Upsilon_{\text{NN}}(S)) \rightarrow (W, \Gamma_{\text{NN}}(S^*))$ is $N_{\text{cut}}N_{\text{ano}}\text{Contra-rg**b}$ -continuous if and only if the inverse image of every $N_{\text{cut}}N_{\text{ano}}$ -closed set in W is $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -open set in U .

Proof. Let V be a $N_{\text{cut}}N_{\text{ano}}$ -closed set in W . Then V^C is $N_{\text{cut}}N_{\text{ano}}$ -open set in W . Since ξ is $N_{\text{cut}}N_{\text{ano}}\text{Contra-rg**b}$ -continuous, $\xi^{-1}(V^C)$ is $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -closed set in U . But $\xi^{-1}(V^C) = (\xi^{-1}(V))^C$ and so $\xi^{-1}(V)$ is $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -open set in U .

Conversely, assume that the inverse image of every $N_{\text{cut}}N_{\text{ano}}$ -closed set in W is $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -open in U . Let G be a $N_{\text{cut}}N_{\text{ano}}$ -open set in W . Then G^C is $N_{\text{cut}}N_{\text{ano}}$ -closed in W . By hypothesis $\xi^{-1}(G^C) = (\xi^{-1}(G))^C$ is $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -open in U , and so $\xi^{-1}(G)$ is $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -closed set in U . Thus ξ is $N_{\text{cut}}N_{\text{ano}}\text{Contra-rg**b}$ -continuous.

Theorem 7.5. If a map $\xi: (U, \Upsilon_{\text{NN}}(S)) \rightarrow (W, \Gamma_{\text{NN}}(S^*))$ is $N_{\text{cut}}N_{\text{ano}}\text{Contra-rg**b}$ -continuous and $\eta: (W, \Gamma_{\text{NN}}(S^*)) \rightarrow (Z, \Psi_{\text{NN}}(S^{**}))$ is $N_{\text{cut}}N_{\text{ano}}$ -continuous, then their composition $\eta \circ \xi: (U, \Upsilon_{\text{NN}}(S)) \rightarrow (Z, \Psi_{\text{NN}}(S^{**}))$ is $N_{\text{cut}}N_{\text{ano}}\text{Contra-rg**b}$ -continuous.

Proof. Let G be a $N_{\text{cut}}N_{\text{ano}}$ -open set in Z . Since η is $N_{\text{cut}}N_{\text{ano}}$ -continuous, $\eta^{-1}(G)$ is $N_{\text{cut}}N_{\text{ano}}$ -open set in W . Since ξ is $N_{\text{cut}}N_{\text{ano}}\text{Contra-rg**b}$ -continuous, $\xi^{-1}[\eta^{-1}(G)]$ is $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -closed set in U . But $(\eta \circ \xi)^{-1}(G) = \xi^{-1}[\eta^{-1}(G)]$. Thus $\eta \circ \xi$ is $N_{\text{cut}}N_{\text{ano}}\text{Contra-rg**b}$ -continuous.

Definition 7.6. A mapping $\xi: (U, \Upsilon_{\text{NN}}(S)) \rightarrow (W, \Gamma_{\text{NN}}(S^*))$ is called $N_{\text{cut}}N_{\text{ano}}\text{Contra-rg**b}$ -irresolute if the inverse image of every $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -open set in W is $N_{\text{cut}}N_{\text{ano}}\text{rg**b}$ -closed in U .

Theorem 7.7. If a mapping $\xi: (U, \Upsilon_{\text{NN}}(S)) \rightarrow (W, \Gamma_{\text{NN}}(S^*))$ is $N_{\text{cut}}N_{\text{ano}}\text{Contra-rg**b}$ -irresolute, then it is $N_{\text{cut}}N_{\text{ano}}\text{Contra-rg**b}$ -continuous.

Proof. Let V be a $N_{cut}N_{ano}$ -open set in W . Since every $N_{cut}N_{ano}$ -open set is $N_{cut}N_{ano}rg^{**}b$ -open, V is $N_{cut}N_{ano}rg^{**}b$ -open set in W . Since ξ is $N_{cut}N_{ano}Contra-rg^{**}b$ -irresolute, $\xi^{-1}(V)$ is $N_{cut}N_{ano}rg^{**}b$ -closed set in U . Thus ξ is $N_{cut}N_{ano}Contra-rg^{**}b$ -continuous.

Theorem 7.8. Let $(U, \Upsilon_{NN}(S))$, $(W, \Gamma_{NN}(S^*))$ and $(Z, \Psi_{NN}(S^{**}))$ be $N_{cut}N_{ano}$ -Top-Spaces. If a function $\xi: (U, \Upsilon_{NN}(S)) \rightarrow (W, \Gamma_{NN}(S^*))$ is $N_{cut}N_{ano}Contra-rg^{**}b$ -irresolute and a function $\eta: (W, \Gamma_{NN}(S^*)) \rightarrow (Z, \Psi_{NN}(S^{**}))$ is $N_{cut}N_{ano}rg^{**}b$ -continuous, then $\eta \circ \xi: (U, \Upsilon_{NN}(S)) \rightarrow (Z, \Psi_{NN}(S^{**}))$ is $N_{cut}N_{ano}Contra-rg^{**}b$ -continuous.

Proof. Let V be any $N_{cut}N_{ano}$ -open set in Z . Since η is $N_{cut}N_{ano}rg^{**}b$ -continuous, $\eta^{-1}(V)$ is $N_{cut}N_{ano}rg^{**}b$ -open set in W . Since ξ is $N_{cut}N_{ano}Contra-rg^{**}b$ -irresolute, $\xi^{-1}[\eta^{-1}(W)]$ is $N_{cut}N_{ano}rg^{**}b$ -closed set in U . But $(\eta \circ \xi)^{-1}(W) = \xi^{-1}[\eta^{-1}(W)]$. Thus $\eta \circ \xi$ is $N_{cut}N_{ano}Contra-rg^{**}b$ -continuous.

Theorem 7.9. If $\xi: (U, \Upsilon_{NN}(S)) \rightarrow (W, \Gamma_{NN}(S^*))$ is $N_{cut}N_{ano}rg^{**}b$ -irresolute and $\eta: (W, \Gamma_{NN}(S^*)) \rightarrow (Z, \Psi_{NN}(S^{**}))$ is $N_{cut}N_{ano}Contra-rg^{**}b$ -irresolute, then their composition $\eta \circ \xi: (U, \Upsilon_{NN}(S)) \rightarrow (Z, \Psi_{NN}(S^{**}))$ is $N_{cut}N_{ano}Contra-rg^{**}b$ -irresolute mapping.

Proof. Let H be any $N_{cut}N_{ano}rg^{**}b$ -open set in Z . Since η is $N_{cut}N_{ano}Contra-rg^{**}b$ -irresolute, $\eta^{-1}(H)$ is $N_{cut}N_{ano}rg^{**}b$ -closed set in W . Since ξ is $N_{cut}N_{ano}rg^{**}b$ -irresolute, $\xi^{-1}[\eta^{-1}(H)]$ is $N_{cut}N_{ano}rg^{**}b$ -closed set in U . But $(\eta \circ \xi)^{-1}(H) = \xi^{-1}[\eta^{-1}(H)]$. Thus $\eta \circ \xi$ is $N_{cut}N_{ano}Contra-rg^{**}b$ -irresolute.

8. Totally Neutrosophic Nano Regular Generalized Star Star B-Continuous Maps

In this section, we introduce totally $N_{cut}N_{ano}rg^{**}b$ -continuous continuous functions and discuss some of their interesting properties.

Definition 8.1. A function $\xi: (U, \Upsilon_{NN}(S)) \rightarrow (W, \Gamma_{NN}(S^*))$ is said to be totally $N_{cut}N_{ano}rg^{**}b$ -continuous if the inverse image of every $N_{cut}N_{ano}$ -closed set in $(W, \Gamma_{NN}(S^*))$ is both $N_{cut}N_{ano}rg^{**}b$ -closed set and $N_{cut}N_{ano}rg^{**}b$ -open set ($\exists, N_{cut}N_{ano}rg^{**}b$ -clopen set) in $(U, \Upsilon_{NN}(S))$.

Theorem 8.2. Every perfectly $N_{cut}N_{ano}rg^{**}b$ -continuous function is totally $N_{cut}N_{ano}rg^{**}b$ -continuous function.

Proof. Let $\xi: (U, \Upsilon_{NN}(S)) \rightarrow (W, \Gamma_{NN}(S^*))$ be a perfectly $N_{cut}N_{ano}rg^{**}b$ -continuous function. Let H be a $N_{cut}N_{ano}$ -closed set in $(W, \Gamma_{NN}(S^*))$. Then H is $N_{cut}N_{ano}rg^{**}b$ -closed in $(W, \Gamma_{NN}(S^*))$. Since ξ is a perfectly $N_{cut}N_{ano}rg^{**}b$ -continuous function, $\xi^{-1}(H)$ is both $N_{cut}N_{ano}$ -closed set and $N_{cut}N_{ano}$ -open set in $(U, \Upsilon_{NN}(S))$. Which implies $\xi^{-1}(H)$ is both $N_{cut}N_{ano}rg^{**}b$ -closed set and $N_{cut}N_{ano}rg^{**}b$ -open set in $(U, \Upsilon_{NN}(S))$. Hence, ξ is totally $N_{cut}N_{ano}rg^{**}b$ -continuous function.

Theorem 8.3. Prove that every totally $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**b}$ -continuous function is $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**b}$ -continuous function.

Proof. Let $\xi: (U, \Upsilon_{\text{NN}}(S)) \rightarrow (W, \Gamma_{\text{NN}}(S^*))$ be a totally $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**b}$ -continuous function. Let H be a $N_{\text{cut}}N_{\text{ano}}$ -closed set in $(W, \Gamma_{\text{NN}}(S^*))$. Since ξ is a totally $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**b}$ -continuous function, $\xi^{-1}(H)$ is both $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**b}$ -closed set and $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**b}$ -open set in $(U, \Upsilon_{\text{NN}}(S))$. Which implies $\xi^{-1}(H)$ is $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**b}$ -closed in $(U, \Upsilon_{\text{NN}}(S))$. Therefore, ξ is $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**b}$ -continuous function.

Definition 8.4. A $N_{\text{cut}}N_{\text{ano}}$ -Top-Space $(U, \Upsilon_{\text{NN}}(S))$ is called a $T_{\text{NN}}\text{rg}^{**b}$ -Space if every $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**b}$ -closed set is $N_{\text{cut}}N_{\text{ano}}$ -closed in $(U, \Upsilon_{\text{NN}}(S))$.

Theorem 8.5. Let $\xi: (U, \Upsilon_{\text{NN}}(S)) \rightarrow (W, \Gamma_{\text{NN}}(S^*))$ be totally $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**b}$ -continuous function and $(W, \Gamma_{\text{NN}}(S^*))$ be $T_{\text{NN}}\text{rg}^{**b}$ -Space. Then ξ is $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**b}$ -irresolute.

Proof. Let H be any $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**b}$ -closed set in $(W, \Gamma_{\text{NN}}(S^*))$. Since $(W, \Gamma_{\text{NN}}(S^*))$ is $T_{\text{NN}}\text{rg}^{**b}$ -Space, H is $N_{\text{cut}}N_{\text{ano}}$ -closed set in $(W, \Gamma_{\text{NN}}(S^*))$. Since ξ is totally $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**b}$ -continuous, $\xi^{-1}(H)$ is both $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**b}$ -closed set and $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**b}$ -open set in $(U, \Upsilon_{\text{NN}}(S))$. Hence $\xi^{-1}(H)$ is $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**b}$ -closed set in $(U, \Upsilon_{\text{NN}}(S))$. Therefore, ξ is $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**b}$ -irresolute.

Theorem 8.6. Let $\xi: (U, \Upsilon_{\text{NN}}(S)) \rightarrow (W, \Gamma_{\text{NN}}(S^*))$ be a $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**b}$ -irresolute function. Let $\eta: (W, \Gamma_{\text{NN}}(S^*)) \rightarrow (Z, \Psi_{\text{NN}}(S^{**}))$ be a totally $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**b}$ -continuous function. Then $(\eta \circ \xi): (U, \Upsilon_{\text{NN}}(S)) \rightarrow (Z, \Psi_{\text{NN}}(S^{**}))$ is totally $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**b}$ -continuous function.

Proof. Let H be a $N_{\text{cut}}N_{\text{ano}}$ -closed set in $(Z, \Psi_{\text{NN}}(S^{**}))$. Since η is totally $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**b}$ -continuous, $\eta^{-1}(H)$ is $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**b}$ -closed set and $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**b}$ -open set in $(W, \Gamma_{\text{NN}}(S^*))$. Since ξ is $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**b}$ -irresolute function, $\xi^{-1}(\eta^{-1}(H)) = (\eta \circ \xi)^{-1}(H)$ is $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**b}$ -closed set and $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**b}$ -open set in $(U, \Upsilon_{\text{NN}}(S))$. Hence $\eta \circ \xi$ is totally $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**b}$ -continuous function.

Theorem 8.7. Let $\xi: (U, \Upsilon_{\text{NN}}(S)) \rightarrow (W, \Gamma_{\text{NN}}(S^*))$ be a totally $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**b}$ -continuous function. Let $\eta: (W, \Gamma_{\text{NN}}(S^*)) \rightarrow (Z, \Psi_{\text{NN}}(S^{**}))$ be a $N_{\text{cut}}N_{\text{ano}}$ -continuous function. Then $(\eta \circ \xi): (U, \Upsilon_{\text{NN}}(S)) \rightarrow (Z, \Psi_{\text{NN}}(S^{**}))$ is totally $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**b}$ -continuous function.

Proof. Let H be a $N_{\text{cut}}N_{\text{ano}}$ -closed set in $(Z, \Psi_{\text{NN}}(S^{**}))$. By hypothesis, $\eta^{-1}(H)$ is a $N_{\text{cut}}N_{\text{ano}}$ -closed set in $(W, \Gamma_{\text{NN}}(S^*))$. Since ξ is totally $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**b}$ -continuous, $\xi^{-1}(\eta^{-1}(H)) = (\eta \circ \xi)^{-1}(H)$ is $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**b}$ -closed set and $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**b}$ -open set in $(U, \Upsilon_{\text{NN}}(S))$. Hence $\eta \circ \xi$ is totally $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**b}$ -continuous function.

Theorem 8.8. Let $\xi: (U, \Upsilon_{\mathbb{NN}}(S)) \rightarrow (W, \Gamma_{\mathbb{NN}}(S^*))$ and $\eta: (W, \Gamma_{\mathbb{NN}}(S^*)) \rightarrow (Z, \Psi_{\mathbb{NN}}(S^{**}))$ be totally $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -continuous functions and $(W, \Gamma_{\mathbb{NN}}(S^*))$ be $T_{\mathbb{NN}}\text{rg}^{**}\mathbf{b}$ -Space. Then $(\eta \circ \xi): (U, \Upsilon_{\mathbb{NN}}(S)) \rightarrow (Z, \Psi_{\mathbb{NN}}(S^{**}))$ is totally $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -continuous function.

Proof. Let H be any $N_{\text{cut}}N_{\text{ano}}$ -closed set in $(Z, \Psi_{\mathbb{NN}}(S^{**}))$. Since η is totally $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -continuous, $\eta^{-1}(H)$ is both $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -closed set and $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -open set in $(W, \Gamma_{\mathbb{NN}}(S^*))$. Since $(W, \Gamma_{\mathbb{NN}}(S^*))$ is $T_{\mathbb{NN}}\text{rg}^{**}\mathbf{b}$ -Space, $\eta^{-1}(H)$ is $N_{\text{cut}}N_{\text{ano}}$ -closed set in $(W, \Gamma_{\mathbb{NN}}(S^*))$. Since ξ is totally $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -continuous, $\xi^{-1}(\eta^{-1}(H)) = (\eta \circ \xi)^{-1}(H)$ is both $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -closed set and $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -open set in $(U, \Upsilon_{\mathbb{NN}}(S))$. Therefore, $\eta \circ \xi$ is totally $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -continuous function.

Conclusion

Neutrosophic set theory has emerged as a powerful tool for handling a wide range of complex problems in engineering, environmental science, economics, and several advanced areas of mathematics. In this research article, we have introduced and studied the properties of $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -continuous functions, $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -irresolute functions, $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -closed functions, $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -open functions, strongly $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -continuous functions, perfectly $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -continuous functions, $N_{\text{cut}}N_{\text{ano}}\text{Contra-rg}^{**}\mathbf{b}$ -continuous functions, $N_{\text{cut}}N_{\text{ano}}\text{Contra-rg}^{**}\mathbf{b}$ -irresolute functions and totally $N_{\text{cut}}N_{\text{ano}}\text{rg}^{**}\mathbf{b}$ -continuous functions in $N_{\text{cut}}N_{\text{ano}}$ -Top-Spaces and established the relations between them. We have obtained fundamental characterizations of these mappings and investigated preservation properties. We expect the results in this paper will be the basis for further applications of mappings in $N_{\text{cut}}N_{\text{ano}}$ -Top-Spaces. The results obtained in this study are expected to serve as a foundation for future investigations and applications of mappings in. Moreover, the findings presented here may contribute to the advancement of information systems and exert a positive influence on related disciplines such as engineering, physics, and computer science. Finally, we hope that this work will inspire further research in neutrosophic topology, paving the way toward the development of a robust and comprehensive framework for practical applications in these fields.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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Author(s) Information

Raja Mohammad Latif

Department of Mathematics and Natural Sciences
Prince Mohammad Bin Fahd University
Al Khobar, Saudi Arabia
ORCID iD: <https://orcid.org/0000-0003-3140-9581>
*Contact e-mail: rlatif@pmu.edu.sa

*Corresponding author(s) email

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Solutions and Solution Behavior of Difference Equation Systems

Naciye Cansu Dikici

Konya Technical University

Dagistan Simsek

Konya Technical University

Abstract: The behaviour of the solutions of the following system of difference equations is examined.

$$x_{n+1} = \max \left\{ \frac{1}{x_{n-2}}, \frac{y_{n-2}}{x_{n-2}} \right\}, y_{n+1} = \max \left\{ \frac{1}{y_{n-2}}, \frac{x_{n-2}}{y_{n-2}} \right\} \quad (1) \quad \text{where the initial conditions are}$$

positive real numbers. In this study, the solutions of the initial conditions in the range (0,1) and the behavior of the solutions were examined. Investigations on the recent studies show that researches nature of nonlinear difference equations have been an object of great interest. Although difference equations are relatively simple in form, it is, unfortunately, extremely difficult to understand thoroughly the periodic and non periodic behavior of their solutions. Nonlinear difference equations of the max type has been investigated by many authors. These equations are particularly utilized in various fields, including population dynamics, economics, finance, and control systems. Max-type difference equations are not only interesting from a theoretical perspective but also possess a wide range of practical applications. They are frequently employed to model discrete dynamical systems in control theory, economic fluctuations, and biological population models with delayed feedback mechanisms. Understanding the periodic behavior and stability of such systems provides vital insights into the long-term dynamics of these real-world phenomena. In addition, Mathematica software was employed to generate the graphical illustrations and numerical examples presented in this study.

Keywords: Difference equation, Maximum operations, Semicycle

Introduction

Recently, there has been a great interest in studying the periodic nature of nonlinear difference equations. Although difference equations are relatively simple in form, it is, unfortunately, extremely difficult to understand thoroughly the periodic behavior of their solutions. The periodic nature of nonlinear difference equations of the max type has been investigated by many authors. See for example [1-28].

Amleh (1998), in her doctoral dissertation conducted under the supervision of G. Ladas, addressed three distinct topics in difference equations. In the first chapter, he demonstrated that the solutions to the difference equation

$$x_{n+1} = \max \left\{ \frac{A}{x_n}, \frac{B}{x_{n-1}} \right\}$$

are periodic for non-zero real parameters and initial conditions.

Janowski et al. (1998), in their study;

$$x_{n+1} = \frac{\max \{x_n^k, A\}}{x_{n-1}}$$

they investigated the boundedness and oscillation properties of solutions to the rational difference equation with maximum.

In his doctoral dissertation, Valicenti (1999) studied the periodicity and global asymptotic stability of solutions to

the Lyness difference equation $x_{n+1} = \frac{\max \{a_n x_n, b_n\}}{x_{n-1}}$ and the difference equation with maximum

$$x_{n+1} = \frac{a_n x_n + b_n}{x_{n-1}}.$$

In his doctoral dissertation, Teixeira (2000) first investigated the periodicity of solutions to the difference equation

$$x_{n+1} = \frac{\max \{x_n, A\}}{x_n x_{n-1}} \text{ where } A \text{ is an arbitrary real number and the initial conditions are non-zero real numbers.}$$

Papaschinopoulos and Hatzifilippidis (2001) examined the continuity, boundedness, and periodicity of positive solutions for the difference equation

$$x_{n+1} = \frac{\max \left\{ a_n \left(\prod_{i=n-k+1}^n x_i \right), b_n \right\}}{\prod_{i=n-k}^n x_i} \text{ assuming positive sequences for the coefficients and positive values for the initial}$$

conditions.

In their study on the periodicity of the difference equation $x_{n+1} = \max \left\{ \frac{A}{x_n}, \frac{B}{x_{n-2}} \right\}$, Mishev et al. (2002) proved

that all positive solutions of the equation are eventually periodic, assuming that the parameters and initial conditions are positive real values.

In the first of his two studies, Voulov (2002) solved an open problem posed by G. Ladas. In this work, he demonstrated that all solutions of the difference equation $x_n = \max \left\{ \frac{A}{x_{n-1}}, \frac{B}{x_{n-3}}, \frac{C}{x_{n-5}} \right\}$ are periodic for

$A + B + C > 0$, assuming the parameters are non-negative real numbers.

Feuer (2003) examined the periodic nature of solutions to the maximum-type Lyness difference equation

$$x_{n+1} = \frac{\max \{x_n^k, A\}}{x_n^\ell x_{n-1}}, \text{ where } A \text{ is a positive real number and both the parameters and initial conditions are taken}$$

as arbitrary real numbers.

In their 2003 study, Papaschinopoulos et al. (2003) investigated the solutions, their periodicity, and the invariant

intervals of the difference equation $x_{n+1} = \frac{\max \{x_n, A\}}{x_n x_{n-1}}$, which had previously been studied by Feuer.

In their study, Patula and Voulov (2004) investigated the periodicity of solutions to the difference equation

$$x_{n+1} = \max \left\{ \frac{A_n}{x_n}, \frac{B_n}{x_{n-2}} \right\}, \text{ where } A_n \text{ and } B_n \text{ are positive sequences with period 3.}$$

In their 2005 study, Çınar et al.(2005) investigated the periodicity of positive solutions to the difference equation

$$x_{n+1} = \min \left\{ \frac{A}{x_n}, \frac{B}{x_{n-2}} \right\}, \text{ for } A, B > 0 \text{ and non-zero initial conditions. Furthermore, they generalized this equation}$$

$$\text{to } x_{n+1} = \min \left\{ \frac{A}{x_n x_{n-1} \dots x_{n-k}}, \frac{B}{x_{n(k+2)} \dots x_{n-(2k+2)}} \right\} \text{ and examined the periodicity of its positive solutions as well.}$$

In their 2006 study, Simsek et al. (2006) investigated the periodicity of solutions to the difference equation

$$x_{n+1} = \max \left\{ \frac{1}{x_{n-1}}, x_{n-1} \right\} \text{ under positive initial conditions.}$$

In their 2009 study, Simsek et al. (2009) investigated the solutions of the system of difference equations with maximum

$$x_{n+1} = \max \left\{ \frac{1}{x_n}, \frac{y_n}{x_n} \right\} \text{ and } y_{n+1} = \max \left\{ \frac{1}{y_n}, \frac{x_n}{y_n} \right\} \text{ by selecting positive initial conditions.}$$

In their 2009 study, Simsek et al. (2009) investigated the solutions of the system of difference equations with maximum

$$x_{n+1} = \max \left\{ \frac{A}{x_n}, \frac{y_n}{x_n} \right\} \text{ and } y_{n+1} = \max \left\{ \frac{A}{y_n}, \frac{x_n}{y_n} \right\} \text{ assuming that both the parameter } A \text{ and the initial conditions are positive.}$$

In their 2010 study, Simsek et al. (2010) investigated the behaviors of solutions for the system of difference equations with maximum

$$x_{n+1} = \max \left\{ \frac{1}{x_{n-1}}, \frac{y_{n-1}}{x_{n-1}} \right\} \text{ and } y_{n+1} = \max \left\{ \frac{1}{y_{n-1}}, \frac{x_{n-1}}{y_{n-1}} \right\} \text{ assuming positive}$$

initial conditions.

$$\text{In their 2006 study, Yan et al. demonstrated that the solutions of the difference equation } x_n = \max \left\{ \frac{1}{x_{n-1}^\alpha}, \frac{A}{x_{n-2}} \right\}$$

are periodic with 4 for the initial conditions $0 < \alpha < 1, A > 0, A \leq 1, A > 1$ and $x_{-2}, x_{-1}, x_0 \in (0, \infty)$.

Definition 1: Let I be an interval of real numbers and let $f: I^{s+1} \rightarrow I$ be a continuously differentiable function where s is a non-negative integer. Consider the difference equation

$$x_{n+1} = f(x_n, x_{n-1}, \dots, x_{n-s}) \text{ for } n = 0, 1, 2, \quad (1)$$

with the initial values $x_{-s}, \dots, x_0 \in I$. A point $\bar{x}$ called an equilibrium point of Eq.(1) if

$$\bar{x} = f(\bar{x}, \dots, \bar{x})$$

Definition 2: A positive semicycle of a solution $\{x_n\}_{n=-s}^\infty$ Eq.(1) consists of a string of terms $\{x_l, x_{l+1}, \dots, x_m\}$ all greater than or equal to equilibrium $\bar{x}$ with $l \geq -s$ and $m \leq \infty$ such that either $l = -s$ or $l > -s$ and $x_{l-1} < \bar{x}$ and either $m = \infty$ or $m \leq \infty$ and $x_{m+1} < \bar{x}$

Definition 3: A negative semicycle of a solution $\{x_n\}_{n=-s}^{\infty}$ of Eq.(1) consists of a string of terms $\{x_l, x_{l+1}, \dots, x_m\}$ all less than or equal to equilibrium $\bar{x}$ with $l \geq -s$ and $m \leq \infty$ such that either $l = -s$ or $l > -s$ and $x_{l-1} < \bar{x}$ and either $m = \infty$ or $m \leq \infty$ and $x_{m+1} < \bar{x}$.

Definition 4: The Fibonacci numbers are defined by the recurrence relation $f_n = f_{n-1} + f_{n-2}$ for $n \geq 3$, with initial conditions $f_1 = 1$ and $f_2 = 1$.

Main Results

To this end, the statements and proofs of lemmas and theorems are presented for various cases that may be encountered in equation (1).

Let $\bar{x}$ and $\bar{y}$ be the unique positive equilibrium of the (1), then clearly

$$\bar{x} = \max \left\{ \frac{1}{\bar{x}}, \frac{\bar{y}}{\bar{x}} \right\} \text{ and } \bar{y} = \max \left\{ \frac{1}{\bar{y}}, \frac{\bar{x}}{\bar{y}} \right\}$$

$$\bar{x} = \frac{1}{\bar{x}} \text{ or } \bar{x} = \frac{\bar{y}}{\bar{x}} \text{ and } \bar{y} = \frac{1}{\bar{y}} \text{ or } \bar{y} = \frac{\bar{x}}{\bar{y}}$$

and

$$(\bar{x})^2 = 1 \text{ and } (\bar{y})^2 = 1$$

We can obtain $\bar{x} = 1$ and $\bar{y} = 1$.

Lemma 1: For equation (1),

$$0 < x_{-2} < x_{-1} < x_0 < y_{-2} < y_{-1} < y_0 < 1$$

the following statements are true for the solutions x_n and y_n with respect to the initial conditions:

- Every positive semicycle consists of three terms.
- Every negative semicycle consists of three terms.
- Solution x_n , every positive semicycle of length three is followed by a negative semicycle of length three.
Solution y_n , for $n \geq 4$; every positive semicycle of length three is followed by a negative semicycle of length three.
- Solution x_n , for $n \geq 4$; every negative semicycle of length three is followed by a positive semicycle of length three. Solution y_n , for $n \geq 7$; every negative semicycle of length three is followed by a positive semicycle of length three.

Proof: Let us present the proof for Case 1.

$$0 < x_{-2} < x_{-1} < x_0 < y_{-2} < y_{-1} < y_0 < 1$$

Depending on the initial conditions:

$$x_1 = \max \left\{ \frac{1}{x_{-2}}, \frac{y_{-2}}{x_{-2}} \right\} = \frac{1}{x_{-2}} > \bar{x}$$

$$y_1 = \max \left\{ \frac{1}{y_{-2}}, \frac{x_{-2}}{y_{-2}} \right\} = \frac{1}{y_{-2}} > \bar{y}$$

$$x_2 = \max \left\{ \frac{1}{x_{-1}}, \frac{y_{-1}}{x_{-1}} \right\} = \frac{1}{x_{-1}} > \bar{x}$$

$$y_2 = \max \left\{ \frac{1}{y_{-1}}, \frac{x_{-1}}{y_{-1}} \right\} = \frac{1}{y_{-1}} > \bar{y}$$

$$x_3 = \max \left\{ \frac{1}{x_0}, \frac{y_0}{x_0} \right\} = \frac{1}{x_0} > \bar{x}$$

$$y_3 = \max \left\{ \frac{1}{y_0}, \frac{x_0}{y_0} \right\} = \frac{1}{y_0} > \bar{y}$$

$$x_4 = \max \left\{ \frac{1}{x_1}, \frac{y_1}{x_1} \right\} = \left\{ x_{-2}, \frac{x_{-2}}{y_{-2}} \right\} = \frac{x_{-2}}{y_{-2}} < \bar{x}$$

$$y_4 = \max \left\{ \frac{1}{y_1}, \frac{x_1}{y_1} \right\} = \left\{ y_{-2}, \frac{y_{-2}}{x_{-2}} \right\} = \frac{y_{-2}}{x_{-2}} > \bar{y}$$

$$x_5 = \max \left\{ \frac{1}{x_2}, \frac{y_2}{x_2} \right\} = \left\{ x_{-1}, \frac{x_{-1}}{y_{-1}} \right\} = \frac{x_{-1}}{y_{-1}} < \bar{x}$$

$$y_5 = \max \left\{ \frac{1}{y_2}, \frac{x_2}{y_2} \right\} = \left\{ y_{-1}, \frac{y_{-1}}{x_{-1}} \right\} = \frac{y_{-1}}{x_{-1}} > \bar{y}$$

$$x_6 = \max \left\{ \frac{1}{x_3}, \frac{y_3}{x_3} \right\} = \left\{ x_0, \frac{x_0^2}{y_0^2} \right\} = \frac{x_0}{y_0} < \bar{x}$$

$$y_6 = \max \left\{ \frac{1}{y_3}, \frac{x_3}{y_3} \right\} = \left\{ y_0, \frac{y_0}{x_0} \right\} = \frac{y_0}{x_0} > \bar{y}$$

$$x_7 = \max \left\{ \frac{1}{x_4}, \frac{y_4}{x_4} \right\} = \left\{ \frac{y_{-2}}{x_{-2}}, \frac{y_{-2}^2}{x_{-2}^2} \right\} = \frac{y_{-2}^2}{x_{-2}^2} > \bar{x}$$

$$y_7 = \max \left\{ \frac{1}{y_4}, \frac{x_4}{y_4} \right\} = \left\{ \frac{x_{-2}}{y_{-2}}, \frac{x_{-2}^2}{y_{-2}^2} \right\} = \frac{x_{-2}}{y_{-2}} < \bar{y}$$

$$x_8 = \max \left\{ \frac{1}{x_5}, \frac{y_5}{x_5} \right\} = \left\{ \frac{y_{-1}}{x_{-1}}, \frac{y_{-1}^2}{x_{-1}^2} \right\} = \frac{y_{-1}^2}{x_{-1}^2} > \bar{x}$$

$$y_8 = \max \left\{ \frac{1}{y_5}, \frac{x_5}{y_5} \right\} = \left\{ \frac{x_{-1}}{y_{-1}}, \frac{x_{-1}^2}{y_{-1}^2} \right\} = \frac{x_{-1}}{y_{-1}} < \bar{y}$$

$$x_9 = \max \left\{ \frac{1}{x_6}, \frac{y_6}{x_6} \right\} = \left\{ \frac{y_0}{x_0}, \frac{y_0^2}{x_0^2} \right\} = \frac{y_0^2}{x_0^2} > \bar{x}$$

$$y_9 = \max \left\{ \frac{1}{y_6}, \frac{x_6}{y_6} \right\} = \left\{ \frac{x_0}{y_0}, \frac{x_0^2}{y_0^2} \right\} = \frac{x_0}{y_0} < \bar{y}$$

$$x_{10} = \max \left\{ \frac{1}{x_7}, \frac{y_7}{x_7} \right\} = \left\{ \frac{x_{-2}^2}{y_{-2}^2}, \frac{x_{-2}^3}{y_{-2}^3} \right\} = \frac{x_{-2}^2}{y_{-2}^2} < \bar{x}$$

$$y_{10} = \max \left\{ \frac{1}{y_7}, \frac{x_7}{y_7} \right\} = \left\{ \frac{y_{-2}}{x_{-2}}, \frac{y_{-2}^3}{x_{-2}^3} \right\} = \frac{y_{-2}^3}{x_{-2}^3} > \bar{y}$$

$$x_{11} = \max \left\{ \frac{1}{x_8}, \frac{y_8}{x_8} \right\} = \left\{ \frac{x_{-1}^2}{y_{-1}^2}, \frac{x_{-1}^3}{y_{-1}^3} \right\} = \frac{x_{-1}^2}{y_{-1}^2} < \bar{x}$$

$$y_{11} = \max \left\{ \frac{1}{y_8}, \frac{x_8}{y_8} \right\} = \left\{ \frac{y_{-1}}{x_{-1}}, \frac{y_{-1}^3}{x_{-1}^3} \right\} = \frac{y_{-1}^3}{x_{-1}^3} > \bar{y}$$

$$x_{12} = \max \left\{ \frac{1}{x_9}, \frac{y_9}{x_9} \right\} = \left\{ \frac{x_0^2}{y_0^2}, \frac{x_0^3}{y_0^3} \right\} = \frac{x_0^2}{y_0^2} < \bar{x}$$

$$y_{12} = \max \left\{ \frac{1}{y_9}, \frac{x_9}{y_9} \right\} = \left\{ \frac{y_0}{x_0}, \frac{y_0^3}{x_0^3} \right\} = \frac{y_0^3}{x_0^3} > \bar{y}$$

⋮

$$x_1 > \bar{x}, x_2 > \bar{x}, x_3 > \bar{x}, x_4 < \bar{x}, x_5 < \bar{x}, x_6 < \bar{x}, x_7 > \bar{x}, x_8 > \bar{x}, x_9 > \bar{x},$$

$$x_{10} < \bar{x}, x_{11} < \bar{x}, x_{12} < \bar{x}, \dots$$

Thus, as can be seen from this, the solutions x_n follow the pattern PPPNNNPPPNNN...

It is observed that every positive semicycle consists of three terms.

It is observed that every negative semicycle consists of three terms.

It is seen from the solutions x_n that every positive semicycle of length three is followed by a negative semicycle of length three.

For $n \geq 4$, every negative semicycle of length three is followed by a positive semicycle of length three.

$$y_1 > \bar{y}, y_2 > \bar{y}, y_3 > \bar{y}, y_4 > \bar{y}, y_5 > \bar{y}, y_6 > \bar{y}, y_7 < \bar{y}, y_8 < \bar{y}, y_9 < \bar{y}, y_{10} > \bar{y}, y_{11} > \bar{y}, y_{12} > \bar{y},$$

Thus, as can be seen from this, the solutions y_n follow the pattern PPNPPPNPPPNPPPN...

It is observed that every positive semicycle consists of three terms.

It is observed that every negative semicycle consists of three terms.

For $n \geq 4$, every positive semicycle of length three is followed by a negative semicycle of length three.

For $n \geq 7$, it is seen from the solutions y_n that every negative semicycle of length three is followed by a positive semicycle of length three.

This completes the proof of Lemma 1.

According to the following initial conditions

$$0 < y_{-2} < x_{-2} < x_{-1} < x_0 < y_{-1} < y_0 < 1, 0 < x_{-2} < x_{-1} < y_0 < x_0 < y_{-2} < y_{-1} < 1,$$

$$0 < y_{-2} < x_{-2} < x_{-1} < y_{-1} < y_0 < x_0 < 1, 0 < x_{-2} < y_{-2} < y_{-1} < x_{-1} < x_0 < y_0 < 1,$$

$$0 < y_{-2} < x_{-2} < y_{-1} < x_{-1} < x_0 < y_0 < 1, 0 < x_{-2} < y_{-2} < y_{-1} < x_{-1} < y_0 < x_0 < 1,$$

$$0 < y_{-2} < x_{-2} < y_{-1} < x_{-1} < y_0 < x_0 < 1.$$

The proof for the solutions x_n and y_n is carried out similarly to the proof of Lemma 1.

Theorem 1: $0 < x_{-2} < x_{-1} < x_0 < y_{-2} < y_{-1} < y_0 < 1$

Where

$$x_1 = \frac{1}{x_{-2}}, x_2 = \frac{1}{x_{-1}}, x_3 = \frac{1}{x_0} \text{ and } y_1 = \frac{1}{y_{-2}}, y_2 = \frac{1}{y_{-1}}, y_3 = \frac{1}{y_0}$$

the solutions of equation (1):

$$\text{a) } x_{6n+4} = \left(\frac{x_{-2}}{y_{-2}} \right)^{f(2n+1)}, x_{6n+5} = \left(\frac{x_{-1}}{y_{-1}} \right)^{f(2n+1)}, x_{6n+6} = \left(\frac{x_0}{y_0} \right)^{f(2n+1)},$$

$$x_{6n+7} = \left(\frac{y_{-2}}{x_{-2}} \right)^{f(2n+3)}, x_{6n+8} = \left(\frac{y_{-1}}{x_{-1}} \right)^{f(2n+3)}, x_{6n+9} = \left(\frac{y_0}{x_0} \right)^{f(2n+3)}$$

$$\text{b) } y_{6n+4} = \left(\frac{y_{-2}}{x_{-2}} \right)^{f(2n+2)}, y_{6n+5} = \left(\frac{y_{-1}}{x_{-1}} \right)^{f(2n+2)}, y_{6n+6} = \left(\frac{y_0}{x_0} \right)^{f(2n+2)},$$

$$y_{6n+7} = \left(\frac{x_{-2}}{y_{-2}} \right)^{f(2n+2)}, y_{6n+8} = \left(\frac{x_{-1}}{y_{-1}} \right)^{f(2n+2)}, y_{6n+9} = \left(\frac{x_0}{y_0} \right)^{f(2n+2)}$$

is of the form. For $n = 0, 1, 2, \dots$, the above equations are true.

Proof: Let us show the validity of the above statements by mathematical induction.

For $n = 0$,

$$x_1 = \max \left\{ \frac{1}{x_{-2}}, \frac{y_{-2}}{x_{-2}} \right\} = \frac{1}{x_{-2}} > \bar{x}$$

$$y_1 = \max \left\{ \frac{1}{y_{-2}}, \frac{x_{-2}}{y_{-2}} \right\} = \frac{1}{y_{-2}} > \bar{y}$$

$$x_2 = \max \left\{ \frac{1}{x_{-1}}, \frac{y_{-1}}{x_{-1}} \right\} = \frac{1}{x_{-1}} > \bar{x}$$

$$y_2 = \max \left\{ \frac{1}{y_{-1}}, \frac{x_{-1}}{y_{-1}} \right\} = \frac{1}{y_{-1}} > \bar{y}$$

$$x_3 = \max \left\{ \frac{1}{x_0}, \frac{y_0}{x_0} \right\} = \frac{1}{x_0} > \bar{x}$$

$$y_3 = \max \left\{ \frac{1}{y_0}, \frac{x_0}{y_0} \right\} = \frac{1}{y_0} > \bar{y}$$

$$x_4 = \max \left\{ \frac{1}{x_1}, \frac{y_1}{x_1} \right\} = \left\{ x_{-2}, \frac{x_{-2}}{y_{-2}} \right\} = \frac{x_{-2}}{y_{-2}} < \bar{x}$$

$$y_4 = \max \left\{ \frac{1}{y_1}, \frac{x_1}{y_1} \right\} = \left\{ y_{-2}, \frac{y_{-2}}{x_{-2}} \right\} = \frac{y_{-2}}{x_{-2}} > \bar{y}$$

$$x_5 = \max \left\{ \frac{1}{x_2}, \frac{y_2}{x_2} \right\} = \left\{ x_{-1}, \frac{x_{-1}}{y_{-1}} \right\} = \frac{x_{-1}}{y_{-1}} < \bar{x}$$

$$y_5 = \max \left\{ \frac{1}{y_2}, \frac{x_2}{y_2} \right\} = \left\{ y_{-1}, \frac{y_{-1}}{x_{-1}} \right\} = \frac{y_{-1}}{x_{-1}} > \bar{y}$$

$$x_6 = \max \left\{ \frac{1}{x_3}, \frac{y_3}{x_3} \right\} = \left\{ x_0, \frac{x_0^2}{y_0^2} \right\} = \frac{x_0}{y_0} < \bar{x}$$

$$y_6 = \max \left\{ \frac{1}{y_3}, \frac{x_3}{y_3} \right\} = \left\{ y_0, \frac{y_0}{x_0} \right\} = \frac{y_0}{x_0} > \bar{y}$$

$$x_7 = \max \left\{ \frac{1}{x_4}, \frac{y_4}{x_4} \right\} = \left\{ \frac{y_{-2}}{x_{-2}}, \frac{y_{-2}^2}{x_{-2}^2} \right\} = \frac{y_{-2}^2}{x_{-2}^2} > \bar{x}$$

$$y_7 = \max \left\{ \frac{1}{y_4}, \frac{x_4}{y_4} \right\} = \left\{ \frac{x_{-2}}{y_{-2}}, \frac{x_{-2}^2}{y_{-2}^2} \right\} = \frac{x_{-2}}{y_{-2}} < \bar{y}$$

$$x_8 = \max \left\{ \frac{1}{x_5}, \frac{y_5}{x_5} \right\} = \left\{ \frac{y_{-1}}{x_{-1}}, \frac{y_{-1}^2}{x_{-1}^2} \right\} = \frac{y_{-1}^2}{x_{-1}^2} > \bar{x}$$

$$y_8 = \max \left\{ \frac{1}{y_5}, \frac{x_5}{y_5} \right\} = \left\{ \frac{x_{-1}}{y_{-1}}, \frac{x_{-1}^2}{y_{-1}^2} \right\} = \frac{x_{-1}}{y_{-1}} < \bar{y}$$

$$x_9 = \max \left\{ \frac{1}{x_6}, \frac{y_6}{x_6} \right\} = \left\{ \frac{y_0}{x_0}, \frac{y_0^2}{x_0^2} \right\} = \frac{y_0^2}{x_0^2} > \bar{x}$$

$$y_9 = \max \left\{ \frac{1}{y_6}, \frac{x_6}{y_6} \right\} = \left\{ \frac{x_0}{y_0}, \frac{x_0^2}{y_0^2} \right\} = \frac{x_0}{y_0} < \bar{y}$$

$$x_{10} = \max \left\{ \frac{1}{x_7}, \frac{y_7}{x_7} \right\} = \left\{ \frac{x_{-2}^2}{y_{-2}^2}, \frac{x_{-2}^3}{y_{-2}^3} \right\} = \frac{x_{-2}^2}{y_{-2}^2} < \bar{x}$$

$$y_{10} = \max \left\{ \frac{1}{y_7}, \frac{x_7}{y_7} \right\} = \left\{ \frac{y_{-2}}{x_{-2}}, \frac{y_{-2}^3}{x_{-2}^3} \right\} = \frac{y_{-2}^3}{x_{-2}^3} > \bar{y}$$

$$x_{11} = \max \left\{ \frac{1}{x_8}, \frac{y_8}{x_8} \right\} = \left\{ \frac{x_{-1}^2}{y_{-1}^2}, \frac{x_{-1}^3}{y_{-1}^3} \right\} = \frac{x_{-1}^2}{y_{-1}^2} < \bar{x}$$

$$y_{11} = \max \left\{ \frac{1}{y_8}, \frac{x_8}{y_8} \right\} = \left\{ \frac{y_{-1}}{x_{-1}}, \frac{y_{-1}^3}{x_{-1}^3} \right\} = \frac{y_{-1}^3}{x_{-1}^3} > \bar{y}$$

$$x_{12} = \max \left\{ \frac{1}{x_9}, \frac{y_9}{x_9} \right\} = \left\{ \frac{x_0^2}{y_0^2}, \frac{x_0^3}{y_0^3} \right\} = \frac{x_0^2}{y_0^2} < \bar{x}$$

$$y_{12} = \max \left\{ \frac{1}{y_9}, \frac{x_9}{y_9} \right\} = \max \left\{ \frac{y_0}{x_0}, \frac{y_0^3}{x_0^3} \right\} = \frac{y_0^3}{x_0^3} > \bar{y}$$

⋮

Assume that the following hold for $n = k$

$$\begin{aligned}
 x_{6k+4} &= \left(\frac{x_{-2}}{y_{-2}} \right)^{f(2k+1)}, & x_{6k+5} &= \left(\frac{x_{-1}}{y_{-1}} \right)^{f(2k+1)}, & x_{6k+6} &= \left(\frac{x_0}{y_0} \right)^{f(2k+1)}, \\
 x_{6k+7} &= \left(\frac{y_{-2}}{x_{-2}} \right)^{f(2k+3)}, & x_{6k+8} &= \left(\frac{y_{-1}}{x_{-1}} \right)^{f(2k+3)}, & x_{6k+9} &= \left(\frac{y_0}{x_0} \right)^{f(2k+3)} \\
 x_{6k+4} &= \left(\frac{y_{-2}}{x_{-2}} \right)^{f(2k+2)}, & x_{6k+5} &= \left(\frac{y_{-1}}{x_{-1}} \right)^{f(2k+2)}, & x_{6k+6} &= \left(\frac{y_0}{x_0} \right)^{f(2k+2)}, \\
 x_{6k+7} &= \left(\frac{x_{-2}}{y_{-2}} \right)^{f(2k+2)}, & x_{6k+8} &= \left(\frac{x_{-1}}{y_{-1}} \right)^{f(2k+2)}, & x_{6k+9} &= \left(\frac{x_0}{y_0} \right)^{f(2k+2)}
 \end{aligned}$$

Now, we show that it is also true for $n = k + 1$

$$\begin{aligned}
 x_{6k+10} &= \max \left\{ \frac{1}{x_{6k+7}}, \frac{y_{6k+7}}{x_{6k+7}} \right\} = \max \left\{ \left(\frac{x_{-2}}{y_{-2}} \right)^{f(2k+3)}, \frac{\left(\frac{x_{-2}}{y_{-2}} \right)^{f(2k+2)}}{\left(\frac{y_{-2}}{x_{-2}} \right)^{f(2k+3)}} \right\} \\
 &= \max \left\{ \left(\frac{x_{-2}}{y_{-2}} \right)^{f(2k+3)}, \left(\frac{x_{-2}}{y_{-2}} \right)^{f(2k+2)} \left(\frac{x_{-2}}{y_{-2}} \right)^{f(2k+3)} \right\} \\
 &= \max \left\{ \left(\frac{x_{-2}}{y_{-2}} \right)^{f(2k+3)}, \left(\frac{x_{-2}}{y_{-2}} \right)^{f(2k+4)} \right\} \\
 &= \left(\frac{x_{-2}}{y_{-2}} \right)^{f(2k+3)},
 \end{aligned}$$

$$\begin{aligned}
 y_{6k+10} &= \max \left\{ \frac{1}{y_{6k+7}}, \frac{x_{6k+7}}{y_{6k+7}} \right\} = \max \left\{ \left(\frac{y_{-2}}{x_{-2}} \right)^{f(2k+2)}, \frac{\left(\frac{y_{-2}}{x_{-2}} \right)^{f(2k+3)}}{\left(\frac{x_{-2}}{y_{-2}} \right)^{f(2k+2)}} \right\} \\
 &= \max \left\{ \left(\frac{y_{-2}}{x_{-2}} \right)^{f(2k+2)}, \left(\frac{y_{-2}}{x_{-2}} \right)^{f(2k+3)} \left(\frac{y_{-2}}{x_{-2}} \right)^{f(2k+2)} \right\} \\
 &= \max \left\{ \left(\frac{y_{-2}}{x_{-2}} \right)^{f(2k+2)}, \left(\frac{y_{-2}}{x_{-2}} \right)^{f(2k+4)} \right\} \\
 &= \left(\frac{y_{-2}}{x_{-2}} \right)^{f(2k+4)},
 \end{aligned}$$

$$\begin{aligned}
 x_{6k+11} &= \max \left\{ \frac{1}{x_{6k+8}}, \frac{y_{6k+8}}{x_{6k+8}} \right\} = \max \left\{ \left(\frac{x_{-1}}{y_{-1}} \right)^{f(2k+3)}, \frac{\left(\frac{x_{-1}}{y_{-1}} \right)^{f(2k+2)}}{\left(\frac{y_{-1}}{x_{-1}} \right)^{f(2k+3)}} \right\} \\
 &= \max \left\{ \left(\frac{x_{-1}}{y_{-1}} \right)^{f(2k+3)}, \left(\frac{x_{-1}}{y_{-1}} \right)^{f(2k+2)} \left(\frac{x_{-1}}{y_{-1}} \right)^{f(2k+3)} \right\} \\
 &= \max \left\{ \left(\frac{x_{-1}}{y_{-1}} \right)^{f(2k+3)}, \left(\frac{x_{-1}}{y_{-1}} \right)^{f(2k+4)} \right\} \\
 &= \left(\frac{x_{-1}}{y_{-1}} \right)^{f(2k+3)},
 \end{aligned}$$

$$\begin{aligned}
 y_{6k+11} &= \max \left\{ \frac{1}{y_{6k+8}}, \frac{x_{6k+8}}{y_{6k+8}} \right\} = \max \left\{ \left(\frac{y_{-1}}{x_{-1}} \right)^{f(2k+2)}, \frac{\left(\frac{y_{-1}}{x_{-1}} \right)^{f(2k+3)}}{\left(\frac{x_{-1}}{y_{-1}} \right)^{f(2k+2)}} \right\} \\
 &= \max \left\{ \left(\frac{y_{-1}}{x_{-1}} \right)^{f(2k+2)}, \left(\frac{y_{-1}}{x_{-1}} \right)^{f(2k+3)} \left(\frac{y_{-1}}{x_{-1}} \right)^{f(2k+2)} \right\} \\
 &= \max \left\{ \left(\frac{y_{-1}}{x_{-1}} \right)^{f(2k+2)}, \left(\frac{y_{-1}}{x_{-1}} \right)^{f(2k+4)} \right\} \\
 &= \left(\frac{y_{-1}}{x_{-1}} \right)^{f(2k+4)},
 \end{aligned}$$

$$\begin{aligned}
 x_{6k+12} &= \max \left\{ \frac{1}{x_{6k+9}}, \frac{y_{6k+9}}{x_{6k+9}} \right\} = \max \left\{ \left(\frac{x_0}{y_0} \right)^{f(2k+2)}, \frac{\left(\frac{x_0}{y_0} \right)^{f(2k+1)}}{\left(\frac{y_0}{x_0} \right)^{f(2k+2)}} \right\} \\
 &= \max \left\{ \left(\frac{x_0}{y_0} \right)^{f(2k+2)}, \left(\frac{x_0}{y_0} \right)^{f(2k+1)} \left(\frac{x_0}{y_0} \right)^{f(2k+2)} \right\} \\
 &= \max \left\{ \left(\frac{x_0}{y_0} \right)^{f(2k+2)}, \left(\frac{x_0}{y_0} \right)^{f(2k+3)} \right\} \\
 &= \left(\frac{x_0}{y_0} \right)^{f(2k+3)},
 \end{aligned}$$

$$\begin{aligned}
 y_{6k+12} &= \max \left\{ \frac{1}{y_{6k+9}}, \frac{x_{6k+9}}{y_{6k+9}} \right\} = \max \left\{ \left(\frac{y_0}{x_0} \right)^{f(2k+2)}, \frac{\left(\frac{y_0}{x_0} \right)^{f(2k+2)}}{\left(\frac{x_0}{y_0} \right)^{f(2k+1)}} \right\} \\
 &= \max \left\{ \left(\frac{y_0}{x_0} \right)^{f(2k+2)}, \left(\frac{y_0}{x_0} \right)^{f(2k+2)} \left(\frac{y_0}{x_0} \right)^{f(2k+1)} \right\} \\
 &= \max \left\{ \left(\frac{y_0}{x_0} \right)^{f(2k+2)}, \left(\frac{y_0}{x_0} \right)^{f(2k+9)} \right\} \\
 &= \left(\frac{y_0}{x_0} \right)^{f(2k+3)},
 \end{aligned}$$

$$\begin{aligned}
 x_{6k+12} &= \max \left\{ \frac{1}{x_{6k+9}}, \frac{y_{6k+9}}{x_{6k+9}} \right\} = \max \left\{ \left(\frac{y_0}{x_0} \right)^{f(2k+2)}, \frac{\left(\frac{x_0}{y_0} \right)^{f(2k+1)}}{\left(\frac{y_0}{x_0} \right)^{f(2k+2)}} \right\} \\
 &= \max \left\{ \left(\frac{y_0}{x_0} \right)^{f(2k+2)}, \left(\frac{y_0}{x_0} \right)^{f(2k+1)} \left(\frac{x_0}{y_0} \right)^{f(2k+2)} \right\} \\
 &= \max \left\{ \left(\frac{y_0}{x_0} \right)^{f(2k+2)}, \left(\frac{x_0}{y_0} \right)^{f(2k+3)} \right\} \\
 &= \left(\frac{y_0}{x_0} \right)^{f(2k+2)},
 \end{aligned}$$

$$\begin{aligned}
 y_{6k+12} &= \max \left\{ \frac{1}{y_{6k+9}}, \frac{x_{6k+9}}{y_{6k+9}} \right\} = \max \left\{ \left(\frac{y_0}{x_0} \right)^{f(2k+1)}, \frac{\left(\frac{y_0}{x_0} \right)^{f(2k+2)}}{\left(\frac{x_0}{y_0} \right)^{f(2k+1)}} \right\} \\
 &= \max \left\{ \left(\frac{y_0}{x_0} \right)^{f(2k+1)}, \left(\frac{y_0}{x_0} \right)^{f(2k+2)} \left(\frac{y_0}{x_0} \right)^{f(2k+1)} \right\} \\
 &= \max \left\{ \left(\frac{y_0}{x_0} \right)^{f(2k+1)}, \left(\frac{y_0}{x_0} \right)^{f(2k+3)} \right\} \\
 &= \left(\frac{y_0}{x_0} \right)^{f(2k+9)},
 \end{aligned}$$

$$\begin{aligned}
 x_{6k+13} &= \max \left\{ \frac{1}{x_{6k+10}}, \frac{y_{6k+10}}{x_{6k+10}} \right\} = \max \left\{ \left(\frac{y_{-2}}{x_{-2}} \right)^{f(2k+2)}, \frac{\left(\frac{y_{-2}}{x_{-2}} \right)^{f(2k+3)}}{\left(\frac{x_{-2}}{y_{-2}} \right)^{f(2k+2)}} \right\} \\
 &= \max \left\{ \left(\frac{y_{-2}}{x_{-2}} \right)^{f(2k+2)}, \left(\frac{y_{-2}}{x_{-2}} \right)^{f(2k+3)} \left(\frac{y_{-2}}{x_{-2}} \right)^{f(2k+4)} \right\} \\
 &= \max \left\{ \left(\frac{y_{-2}}{x_{-2}} \right)^{f(2k+2)}, \left(\frac{y_{-2}}{x_{-2}} \right)^{f(2k+4)} \right\} \\
 &= \left(\frac{y_{-2}}{x_{-2}} \right)^{f(2k+4)},
 \end{aligned}$$

$$\begin{aligned}
 y_{6k+13} &= \max \left\{ \frac{1}{y_{6k+10}}, \frac{x_{6k+10}}{y_{6k+10}} \right\} = \max \left\{ \left(\frac{x_{-2}}{y_{-2}} \right)^{f(2k+3)}, \frac{\left(\frac{x_{-2}}{y_{-2}} \right)^{f(2k+2)}}{\left(\frac{y_{-2}}{x_{-2}} \right)^{f(2k+3)}} \right\} \\
 &= \max \left\{ \left(\frac{x_{-2}}{y_{-2}} \right)^{f(2k+3)}, \left(\frac{x_{-2}}{y_{-2}} \right)^{f(2k+2)} \left(\frac{x_{-2}}{y_{-2}} \right)^{f(2k+3)} \right\} \\
 &= \max \left\{ \left(\frac{x_{-2}}{y_{-2}} \right)^{f(2k+3)}, \left(\frac{x_{-2}}{y_{-2}} \right)^{f(2k+4)} \right\} \\
 &= \left(\frac{x_{-2}}{y_{-2}} \right)^{f(2k+3)},
 \end{aligned}$$

$$\begin{aligned}
 x_{6k+14} &= \max \left\{ \frac{1}{x_{6k+11}}, \frac{y_{6k+11}}{x_{6k+11}} \right\} = \max \left\{ \left(\frac{y_{-1}}{x_{-1}} \right)^{f(2k+2)}, \frac{\left(\frac{y_{-1}}{x_{-1}} \right)^{f(2k+3)}}{\left(\frac{x_{-1}}{y_{-1}} \right)^{f(2k+4)}} \right\} \\
 &= \max \left\{ \left(\frac{y_{-1}}{x_{-1}} \right)^{f(2k+2)}, \left(\frac{y_{-1}}{x_{-1}} \right)^{f(2k+3)} \left(\frac{y_{-1}}{x_{-1}} \right)^{f(2k+2)} \right\} \\
 &= \max \left\{ \left(\frac{y_{-1}}{x_{-1}} \right)^{f(2k+2)}, \left(\frac{y_{-1}}{x_{-1}} \right)^{f(2k+4)} \right\} \\
 &= \left(\frac{y_{-1}}{x_{-1}} \right)^{f(2k+4)},
 \end{aligned}$$

and

$$\begin{aligned}
 y_{6k+14} &= \max \left\{ \frac{1}{y_{6k+11}}, \frac{x_{6k+11}}{y_{6k+11}} \right\} = \max \left\{ \left(\frac{x_{-1}}{y_{-1}} \right)^{f(2k+3)}, \frac{\left(\frac{x_{-1}}{y_{-1}} \right)^{f(2k+2)}}{\left(\frac{y_{-1}}{x_{-1}} \right)^{f(2k+3)}} \right\} \\
 &= \max \left\{ \left(\frac{x_{-1}}{y_{-1}} \right)^{f(2k+3)}, \left(\frac{x_{-1}}{y_{-1}} \right)^{f(2k+2)} \left(\frac{x_{-1}}{y_{-1}} \right)^{f(2k+3)} \right\} \\
 &= \max \left\{ \left(\frac{x_{-1}}{y_{-1}} \right)^{f(2k+3)}, \left(\frac{x_{-1}}{y_{-1}} \right)^{f(2k+4)} \right\} \\
 &= \left(\frac{x_{-1}}{y_{-1}} \right)^{f(2k+3)}
 \end{aligned}$$

$$\begin{aligned}
 x_{6k+15} &= \max \left\{ \frac{1}{x_{6k+12}}, \frac{y_{6k+12}}{x_{6k+12}} \right\} = \max \left\{ \left(\frac{y_0}{x_0} \right)^{f(2k+2)}, \frac{\left(\frac{y_0}{x_0} \right)^{f(2k+3)}}{\left(\frac{x_0}{y_0} \right)^{f(2k+2)}} \right\} \\
 &= \max \left\{ \left(\frac{y_0}{x_0} \right)^{f(2k+2)}, \left(\frac{y_0}{x_0} \right)^{f(2k+3)} \left(\frac{y_0}{x_0} \right)^{f(2k+2)} \right\} \\
 &= \max \left\{ \left(\frac{y_0}{x_0} \right)^{f(2k+2)}, \left(\frac{x_0}{y_0} \right)^{f(2k+4)} \right\} \\
 &= \left(\frac{y_0}{x_0} \right)^{f(2k+4)},
 \end{aligned}$$

$$\begin{aligned}
 y_{6k+15} &= \max \left\{ \frac{1}{y_{6k+12}}, \frac{x_{6k+12}}{y_{6k+12}} \right\} = \max \left\{ \left(\frac{x_0}{y_0} \right)^{f(2k+3)}, \frac{\left(\frac{x_0}{y_0} \right)^{f(2k+2)}}{\left(\frac{y_0}{x_0} \right)^{f(2k+3)}} \right\} \\
 &= \max \left\{ \left(\frac{x_0}{y_0} \right)^{f(2k+3)}, \left(\frac{x_0}{y_0} \right)^{f(2k+2)} \left(\frac{x_0}{y_0} \right)^{f(2k+3)} \right\} \\
 &= \max \left\{ \left(\frac{x_0}{y_0} \right)^{f(2k+3)}, \left(\frac{x_0}{y_0} \right)^{f(2k+4)} \right\} \\
 &= \left(\frac{x_0}{y_0} \right)^{f(2k+3)},
 \end{aligned}$$

is obtained. Thus, the validity of the above statements is established by mathematical induction.

According to the following initial conditions

$$0 < y_{-2} < x_{-2} < x_{-1} < x_0 < y_{-1} < y_0 < 1, \quad 0 < x_{-2} < x_{-1} < y_0 < x_0 < y_{-2} < y_{-1} < 1,$$

$$0 < y_{-2} < x_{-2} < x_{-1} < y_{-1} < y_0 < x_0 < 1, \quad 0 < x_{-2} < y_{-2} < y_{-1} < x_{-1} < x_0 < y_0 < 1,$$

$$0 < y_{-2} < x_{-2} < y_{-1} < x_{-1} < x_0 < y_0 < 1, \quad 0 < x_{-2} < y_{-2} < y_{-1} < x_{-1} < y_0 < x_0 < 1,$$

$$0 < y_{-2} < x_{-2} < y_{-1} < x_{-1} < y_0 < x_0 < 1.$$

The proof for the solutions x_n and y_n is obtained similarly to the proof of Theorem 1.

Theorem 2: (1) System of equations,

$$0 < x_{-2} < x_{-1} < x_0 < y_{-2} < y_{-1} < y_0 < 1$$

Depending on the initial condition

$$\begin{aligned} \lim_{n \rightarrow \infty} x_{6n+1} &= \infty, \quad \lim_{n \rightarrow \infty} x_{6n+2} = \infty, \quad \lim_{n \rightarrow \infty} x_{6n+3} = \infty, \\ \text{a) } \lim_{n \rightarrow \infty} x_{6n+4} &= 0, \quad \lim_{n \rightarrow \infty} x_{6n+5} = 0, \quad \lim_{n \rightarrow \infty} x_{6n+6} = 0, \\ \lim_{n \rightarrow \infty} x_{6n+7} &= \infty, \quad \lim_{n \rightarrow \infty} x_{6n+8} = \infty, \quad \lim_{n \rightarrow \infty} x_{6n+9} = \infty \end{aligned}$$

$$\begin{aligned} \lim_{n \rightarrow \infty} y_{6n+1} &= \infty, \quad \lim_{n \rightarrow \infty} y_{6n+2} = \infty, \quad \lim_{n \rightarrow \infty} y_{6n+3} = \infty, \\ \text{b) } \lim_{n \rightarrow \infty} y_{6n+4} &= \infty, \quad \lim_{n \rightarrow \infty} y_{6n+5} = \infty, \quad \lim_{n \rightarrow \infty} y_{6n+6} = \infty, \\ \lim_{n \rightarrow \infty} y_{6n+7} &= 0, \quad \lim_{n \rightarrow \infty} y_{6n+8} = 0, \quad \lim_{n \rightarrow \infty} y_{6n+9} = 0 \end{aligned}$$

Proof:

a) We obtain,

$$\text{For } 0 < x_{-2} < 1, \quad \lim_{n \rightarrow \infty} x_{6n+1} = \lim_{n \rightarrow \infty} \left(\frac{1}{x_{-2}} \right) = \frac{1}{x_{-2}} = \infty$$

$$\text{For } 0 < x_{-1} < 1, \quad \lim_{n \rightarrow \infty} x_{6n+2} = \lim_{n \rightarrow \infty} \left(\frac{1}{x_{-1}} \right) = \frac{1}{x_{-1}} = \infty$$

$$\text{For } 0 < x_0 < 1, \quad \lim_{n \rightarrow \infty} x_{6n+3} = \lim_{n \rightarrow \infty} \left(\frac{1}{x_0} \right) = \frac{1}{x_0} = \infty$$

$$\text{For } 0 < x_{-2} < y_{-2} < 1, \quad \lim_{n \rightarrow \infty} x_{6n+4} = \lim_{n \rightarrow \infty} \left(\frac{x_{-2}}{y_{-2}} \right)^{f(2n+1)} = \left(\frac{x_{-2}}{y_{-2}} \right)^{f(\infty)} = \left(\frac{x_{-2}}{y_{-2}} \right)^\infty = 0$$

$$\text{For } 0 < x_{-1} < y_{-1} < 1, \quad \lim_{n \rightarrow \infty} x_{6n+5} = \lim_{n \rightarrow \infty} \left(\frac{x_{-1}}{y_{-1}} \right)^{f(2n+1)} = \left(\frac{x_{-1}}{y_{-1}} \right)^{f(\infty)} = \left(\frac{x_{-1}}{y_{-1}} \right)^\infty = 0$$

$$\text{For } 0 < x_0 < y_0 < 1, \quad \lim_{n \rightarrow \infty} x_{6n+6} = \lim_{n \rightarrow \infty} \left(\frac{x_0}{y_0} \right)^{f(2n+1)} = \left(\frac{x_0}{y_0} \right)^{f(\infty)} = \left(\frac{x_0}{y_0} \right)^{\infty} = 0$$

$$\text{For } 0 < x_{-2} < y_{-2} < 1, \quad \lim_{n \rightarrow \infty} x_{6n+7} = \lim_{n \rightarrow \infty} \left(\frac{y_{-2}}{x_{-2}} \right)^{f(2n+3)} = \left(\frac{y_{-2}}{x_{-2}} \right)^{f(\infty)} = \left(\frac{y_{-2}}{x_{-2}} \right)^{\infty} = \infty$$

$$\text{For } 0 < x_{-1} < y_{-1} < 1, \quad \lim_{n \rightarrow \infty} x_{6n+8} = \lim_{n \rightarrow \infty} \left(\frac{y_{-1}}{x_{-1}} \right)^{f(2n+3)} = \left(\frac{y_{-1}}{x_{-1}} \right)^{f(\infty)} = \left(\frac{y_{-1}}{x_{-1}} \right)^{\infty} = \infty$$

$$\text{For } 0 < x_0 < y_0 < 1, \quad \lim_{n \rightarrow \infty} x_{6n+9} = \lim_{n \rightarrow \infty} \left(\frac{y_0}{x_0} \right)^{f(2n+3)} = \left(\frac{y_0}{x_0} \right)^{f(\infty)} = \left(\frac{y_0}{x_0} \right)^{\infty} = \infty$$

b) We obtain

$$\text{For } 0 < y_{-2} < 1, \quad \lim_{n \rightarrow \infty} y_{6n+1} = \lim_{n \rightarrow \infty} \left(\frac{1}{y_{-2}} \right) = \frac{1}{y_{-2}} = \infty$$

$$\text{For } 0 < y_{-1} < 1, \quad \lim_{n \rightarrow \infty} y_{6n+2} = \lim_{n \rightarrow \infty} \left(\frac{1}{y_{-1}} \right) = \frac{1}{y_{-1}} = \infty$$

$$\text{For } 0 < y_0 < 1, \quad \lim_{n \rightarrow \infty} y_{6n+3} = \lim_{n \rightarrow \infty} \left(\frac{1}{y_0} \right) = \frac{1}{y_0} = \infty$$

$$\text{For } 0 < x_{-2} < y_{-2} < 1, \quad \lim_{n \rightarrow \infty} y_{6n+4} = \lim_{n \rightarrow \infty} \left(\frac{y_{-2}}{x_{-2}} \right)^{f(2n+2)} = \left(\frac{y_{-2}}{x_{-2}} \right)^{f(\infty)} = \left(\frac{y_{-2}}{x_{-2}} \right)^{\infty} = \infty$$

$$\text{For } 0 < x_{-1} < y_{-1} < 1, \quad \lim_{n \rightarrow \infty} y_{6n+5} = \lim_{n \rightarrow \infty} \left(\frac{y_{-1}}{x_{-1}} \right)^{f(2n+2)} = \left(\frac{y_{-1}}{x_{-1}} \right)^{f(\infty)} = \left(\frac{y_{-1}}{x_{-1}} \right)^{\infty} = \infty$$

$$\text{For } 0 < x_0 < y_0 < 1, \quad \lim_{n \rightarrow \infty} y_{6n+6} = \lim_{n \rightarrow \infty} \left(\frac{y_0}{x_0} \right)^{f(2n+2)} = \left(\frac{y_0}{x_0} \right)^{f(\infty)} = \left(\frac{y_0}{x_0} \right)^{\infty} = \infty$$

$$\text{For } 0 < x_{-2} < y_{-2} < 1, \quad \lim_{n \rightarrow \infty} y_{6n+7} = \lim_{n \rightarrow \infty} \left(\frac{x_{-2}}{y_{-2}} \right)^{f(2n+2)} = \left(\frac{x_{-2}}{y_{-2}} \right)^{f(\infty)} = \left(\frac{x_{-2}}{y_{-2}} \right)^{\infty} = 0$$

$$\text{For } 0 < x_{-1} < y_{-1} < 1, \quad \lim_{n \rightarrow \infty} y_{6n+8} = \lim_{n \rightarrow \infty} \left(\frac{x_{-1}}{y_{-1}} \right)^{f(2n+2)} = \left(\frac{x_{-1}}{y_{-1}} \right)^{f(\infty)} = \left(\frac{x_{-1}}{y_{-1}} \right)^{\infty} = 0$$

$$\text{For } 0 < x_0 < y_0 < 1, \quad \lim_{n \rightarrow \infty} y_{6n+9} = \lim_{n \rightarrow \infty} \left(\frac{x_0}{y_0} \right)^{f(2n+2)} = \left(\frac{x_0}{y_0} \right)^{f(\infty)} = \left(\frac{x_0}{y_0} \right)^{\infty} = 0.$$

According to the following initial conditions

$$0 < y_{-2} < x_{-2} < x_{-1} < x_0 < y_{-1} < y_0 < 1, \quad 0 < x_{-2} < x_{-1} < y_0 < x_0 < y_{-2} < y_{-1} < 1,$$

$$0 < y_{-2} < x_{-2} < x_{-1} < y_{-1} < y_0 < x_0 < 1, \quad 0 < x_{-2} < y_{-2} < y_{-1} < x_{-1} < x_0 < y_0 < 1,$$

$$0 < y_{-2} < x_{-2} < y_{-1} < x_{-1} < x_0 < y_0 < 1, \quad 0 < x_{-2} < y_{-2} < y_{-1} < x_{-1} < y_0 < x_0 < 1,$$

$$0 < y_{-2} < x_{-2} < y_{-1} < x_{-1} < y_0 < x_0 < 1$$

The proof for the solutions x_n and y_n is obtained similarly to the proof of Theorem 2.

EXAMPLE 1: If the initial conditions are selected as follows:

$$x[-2]=0.2; x[-1]=0.3; x[0]=0.4; y[-2]=0.5; y[-1]=0.6; y[0]=0.7;$$

then the following solutions are obtained:

$$x(n)=\{5.,3.3333333333333335,2.5,0.4,0.5,0.5714285714285715,6.25,4.,3.0624999999999996,0.16,0.25,0.326530612244898,97.65625,32.,16.413085937499996,0.01024,\dots\}$$

$$y(n)=\{2.,1.6666666666666667,1.4285714285714286,2.5,2.,1.75,0.4,0.5,0.5714285714285714,15.625,8.,5.359374999999999,0.064,0.125,0.18658892128279886,1525.87890625,\dots\}$$

The graph of the solutions is given below.

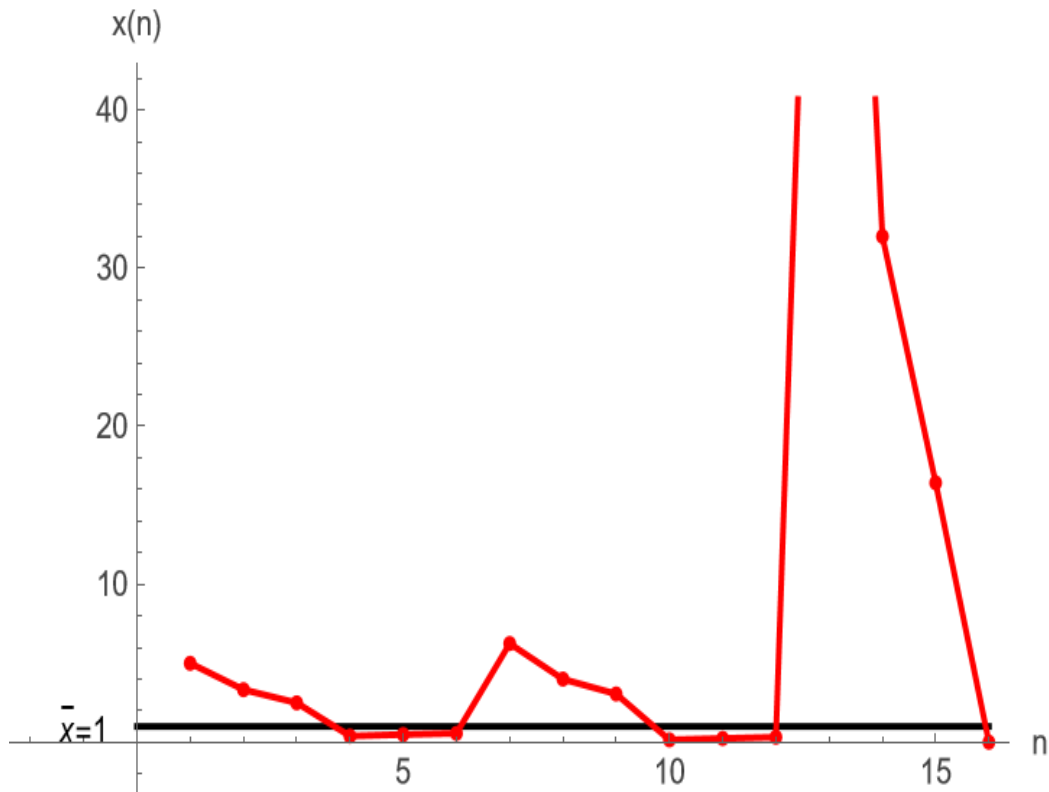


Figure 1. $x(n)$ graph of the solutions

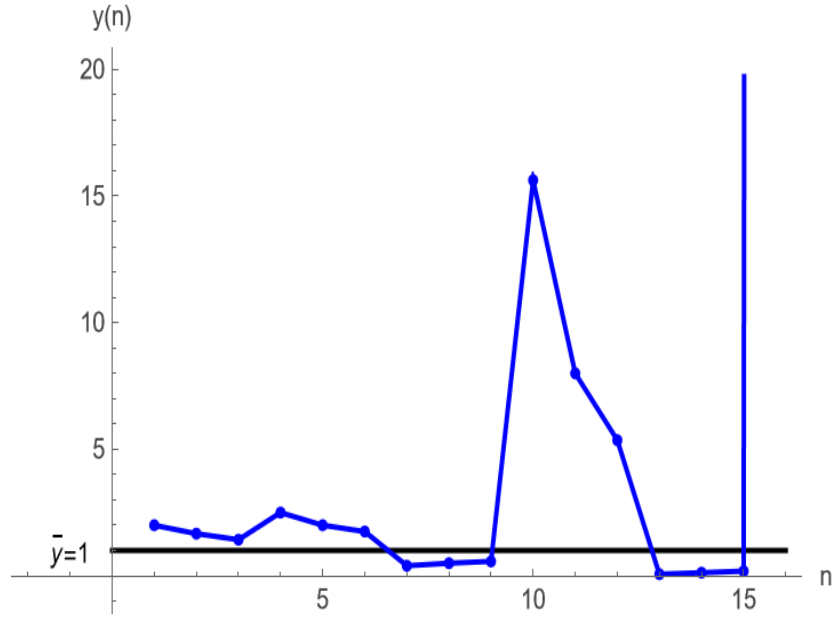


Figure 2. $y(n)$ graph of the solutions

EXAMPLE 2: If the initial conditions are selected as follows:

$$x[-2]=0.02; x[-1]=0.03; x[0]=0.04; y[-2]=0.05; y[-1]=0.06; y[0]=0.07;$$

then the following solutions are obtained:

$$x(n)=\{50.,33.333333333333336,25.,0.4,0.5,0.5714285714285714,6.25,4.,3.0625000000000004,0.16,0.25,0.32653061224489793,97.65625,32.,16.413085937500004,0.01024,\dots\}$$

$$y(n)=\{20.,16.666666666666668,14.285714285714285,2.5,2.,1.7500000000000002,0.4,0.5,0.5714285714285714,15.625,8.,5.359375000000001,0.064,0.125,0.1865889212827988,1525.87890625,\dots\}$$

The graph of the solutions is given below.

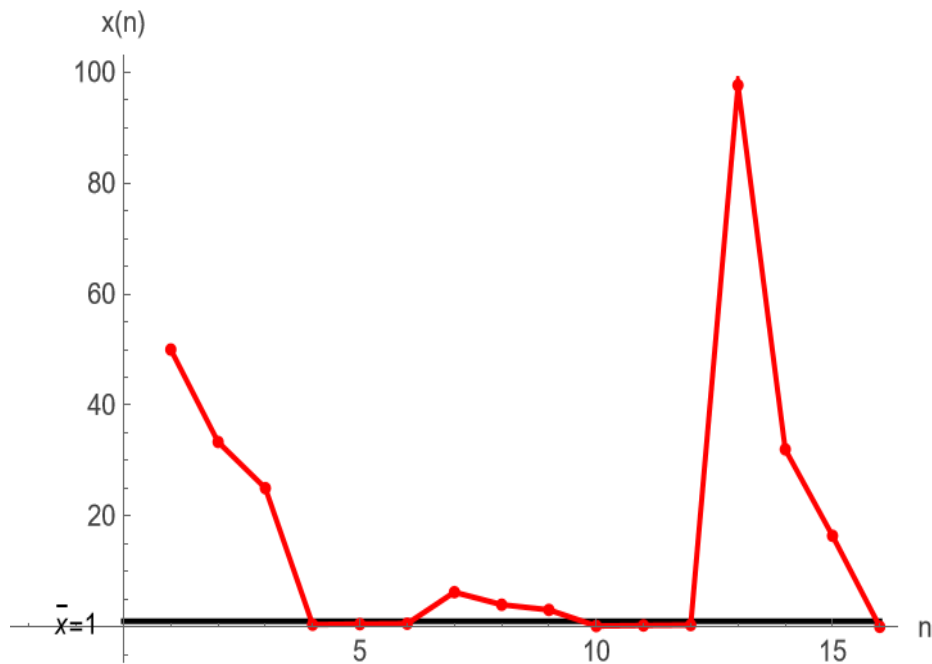


Figure 3. $x(n)$ graph of the solutions

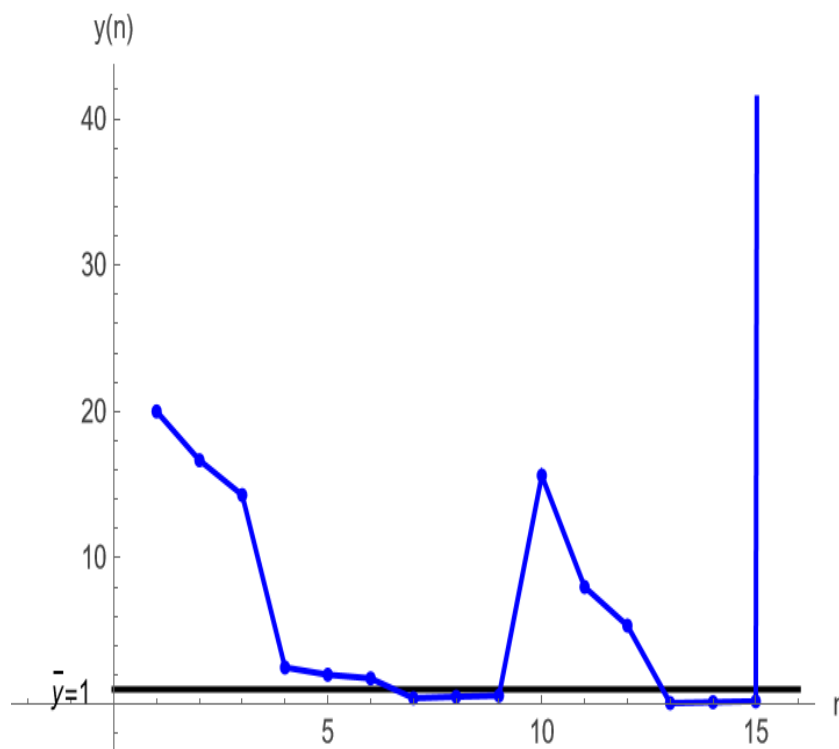


Figure 4. $y(n)$ graph of the solutions

Conclusion

Given that the initial conditions x_{-2}, x_{-1}, x_0 are positive real numbers,

$$x_{n+1} = \max \left\{ \frac{1}{x_{n-2}}, \frac{y_{n-2}}{x_{n-2}} \right\}, y_{n+1} = \max \left\{ \frac{1}{y_{n-2}}, \frac{x_{n-2}}{y_{n-2}} \right\}$$

the behavior of the solutions for the system of

max-type difference equations has been investigated.

$$x_{n+1} = \max \left\{ \frac{1}{x_{n-k}}, \frac{y_{n-k}}{x_{n-k}} \right\}, y_{n+1} = \max \left\{ \frac{1}{y_{n-k}}, \frac{x_{n-k}}{y_{n-k}} \right\}$$

For future studies, researchers may investigate the solutions of the newly constructed system of difference equations, for various values of k .

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that there is no conflict of interest

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Author(s) Information

Naciye Cansu Dikici

Konya Technical University
Institute of Graduate Studies, Konya, Türkiye
ORCID iD: <https://orcid.org/000-0009-8216-6111>
*Contact e-mail: cansudikici20@gmail.com

Dagistan Simsek

Konya Technical University
Faculty of Engineering and Natural Sciences, Konya,
Türkiye
ORCID iD: <https://orcid.org/0000-0003-3003-807X>

*Corresponding author(s) contact email

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On the Incompleted Sequences

Ebru Sena Kurt

Konya Technical University

Nurettin Irmak

Konya Technical University

Abstract: In this study, Fibonacci, Lucas, and generalized forms of these sequences are examined. In the first chapter, definitions of Fibonacci and Lucas number sequences are provided, and some of their properties are analyzed. In the second chapter, incomplete Fibonacci and Lucas numbers are analyzed. Finally, in the third chapter, incomplete Fibonacci and Lucas numbers with arithmetic indices are defined and new relations are obtained

Keywords: Sequences with arithmetic indices, Fibonacci, Lucas, Incomplete Fibonacci and Lucas sequences

Introduction

Fibonacci Sequence

Let F_n denote the n . term of the Fibonacci sequence; for $n \geq 3$ under the initial conditions $F_1 = 1, F_2 = 1$ numbers satisfying this relation are called Fibonacci numbers (Koshy, 2001).

$$F_n = F_{n-1} + F_{n-2} \quad (1.1)$$

According to this definition, the first few Fibonacci numbers are as follows:

$$F_0 = 0$$

$$F_1 = 1$$

$$F_2 = 1$$

$$F_3 = F_2 + F_1 = 1 + 1 = 2$$

$$F_4 = F_3 + F_2 = 2 + 1 = 3$$

$$F_5 = F_4 + F_3 = 3 + 2 = 5$$

$$F_6 = F_5 + F_4 = 5 + 3 = 8$$

Binet Formula

Let $\alpha = \frac{1+\sqrt{5}}{2}$ and $\beta = \frac{1-\sqrt{5}}{2}$. Since each term of the Fibonacci sequence can be written as a linear combination of α and β , we obtain the equation

$$F_n = A\alpha^n + B\beta^n \quad (1.2)$$

When the initial conditions are substituted into this equation,

$$F_0 = A + B = 0$$

if the expression $B = -A$ is substituted,

$$F_1 = A\alpha + B\beta = 1$$

$$= A\alpha + (-A)\beta = 0$$

$$= A(\alpha - \beta) = 1$$

$$A = \frac{1}{\alpha - \beta} \quad B = -\frac{1}{\alpha - \beta}$$

When the coefficients A and B are substituted into equation (1.2),

$$F_n = \left(\frac{1}{\alpha - \beta}\right)\alpha^n + \left(\frac{-1}{\alpha - \beta}\right)\beta^n$$

$$F_n = \frac{\alpha^n - \beta^n}{\alpha - \beta}$$

is obtained, and this equation we have found is called the Binet Formula (Koshy, 2001).

Some Properties of Fibonacci Numbers

In this section, we will examine a few of the most important of the many mathematical relationships presented by Fibonacci numbers. In particular, our next property will play a central role in the proofs of these relationships (Koshy, 2001). It is well-known that

$$\sum_{k=0}^n x^k = \frac{1-x^{(n+1)}}{1-x} \text{ and } x < 1, n \rightarrow \infty, \sum_{k=0}^{\infty} x^k = \frac{1}{1-x}.$$

- The sum of consecutive Fibonacci numbers is expressed as follows.

$$\sum_{i=0}^n F_i = F_{n+2} - 1$$

Proof: Let us perform the proof using the Binet formula.

$$\begin{aligned}
 \sum_{i=1}^n F_i &= \sum_{i=1}^n \frac{\alpha^i - \beta^i}{\alpha - \beta} \\
 &= \frac{1}{\alpha - \beta} \left(\sum_{i=1}^n \alpha^i - \sum_{i=1}^n \beta^i \right) \\
 &= \frac{1}{\alpha - \beta} \left(\sum_{i=0}^{n-1} \alpha^{i+1} - \sum_{i=0}^{n-1} \beta^{i+1} \right) \\
 &= \frac{1}{\alpha - \beta} \left(\alpha \frac{1 - \alpha^n}{1 - \alpha} - \beta \frac{1 - \beta^n}{1 - \beta} \right)
 \end{aligned}$$

When the inequalities $\alpha + \beta = 1, \alpha\beta = -1$ are used,

$$\begin{aligned}
 &= \frac{1}{\alpha - \beta} (-\alpha^2(1 - \alpha^n) + \beta^2 - (1 - \beta^n)) \\
 &= \frac{1}{\alpha - \beta} (\alpha^{n+2} - \beta^{n+2} - (\alpha^2 - \beta^2)) \\
 &= \frac{\alpha^{n+2} - \beta^{n+2}}{\alpha - \beta} - \frac{(\alpha - \beta)(\alpha + \beta)}{\alpha - \beta} \\
 &= F_{n+2} - 1
 \end{aligned}$$

- For every integer $n \geq 1$ the following equations are obtained (Koshy, 2001).

$$\begin{aligned}
 \sum_{i=1}^n F_{2i-1} &= F_{2n} \\
 \sum_{i=1}^n F_{2i} &= F_{2n+1} - 1
 \end{aligned}$$

Proof:

$$\begin{aligned}
 \sum_{i=1}^n F_{2i-1} &= \sum_{i=1}^n \frac{\alpha^{2i-1} - \beta^{2i-1}}{\alpha - \beta} \\
 &= \frac{1}{\alpha - \beta} \left(\alpha \sum_{i=1}^n \alpha^{2i} - \beta \sum_{i=1}^n \beta^{2i} \right) \\
 &= \frac{1}{\alpha - \beta} \left(\alpha \frac{1 - \alpha^{2n}}{(1 - \alpha)(1 - \beta)} - \beta \frac{1 - \beta^{2n}}{(1 - \alpha)(1 - \beta)} \right)
 \end{aligned}$$

$$\begin{aligned}
 &= \frac{1}{\alpha - \beta} \left(-\alpha^2 \frac{1 - \alpha^{2n}}{1 + \alpha} + \beta^2 \frac{1 - \beta^{2n}}{1 + \beta} \right) \\
 &= \frac{1}{\alpha - \beta} (-1 + \alpha^{2n} + 1 - \beta^{2n}) \\
 &= \frac{\alpha^{2n} - \beta^{2n}}{\alpha - \beta}
 \end{aligned}$$

- For every natural number $n \geq 1$ two consecutive Fibonacci numbers are coprime (relatively prime) (Koshy, 2001).

$$(F_{n+1}, F_n) = 1$$

Proof: By induction. It is obvious that, for $n=1$,

$$(F_2, F_1) = (1, 1) = 1$$

Assume it is true for $n=k$. Namely,

$$(F_{k+1}, F_k) = 1.$$

Is it true for $n=k+1$? Let $(F_{k+2}, F_{k+1}) = d$. Since $d \mid F_{k+2}$, $d \mid F_{k+1}$ and $F_k = F_{k+2} - F_{k+1}$ it follows that $d \mid (F_{k+2} - F_{k+1})$. Thus, $d \mid F_k$ is obtained. $d \leq (F_{k+1}, F_k)$, that is, $d \leq 1$. Since $d \geq 1$ by the definition of the GCD $d = 1$ is obtained. $(F_{k+2}, F_{k+1}) = 1$ is found.

- For every natural number $n \geq 1$ (Koshy, 2001).

$$F_{n+1}F_{n-1} - F_n^2 = (-1)^n$$

Proof: Let us solve it using the method of induction.

$$n = 1$$

$$F_0F_2 - F_1 = 0 * 1 - 1^2 = (-1)^2$$

Assume it is true for $n=k$.

$$F_{k-1}F_{k+1} - F_k^2 = (-1)^k$$

Is it true for $n=k+1$?

$$F_kF_{k+2} - F_{k+1}^2 = (-1)^{(k+1)}$$

$$= (F_{k+1} - F_{k-1})(F_k + F_{k+1}) - F_{k+1}^2$$

$$= F_{k+1}F_k + F_{k+1}^2 - F_{k-1}F_k - F_{k-1}F_{k+1} - F_{k+1}^2$$

$$\begin{aligned}
 &= F_{k+1}F_k - F_{k-1}F_k - F_k^2 - (-1)^k \\
 &= F_kF_{k+1} - F_k(F_{k-1} + F_k) + (-1)^{(k+1)} \\
 &= F_kF_{k+1} - F_kF_{k+1} + (-1)^{(k+1)} \\
 &= (-1)^{(k+1)}
 \end{aligned}$$

follows as claimed.

Lucas (Companion) Sequence

When Fibonacci numbers are mentioned, another closely related important number sequence that comes to mind is the Lucas numbers. The terms of this sequence are denoted by L_n . Lucas numbers use exactly the same recurrence relation as Fibonacci numbers, but they have different initial conditions (Koshy, 2001).

With the initial conditions being $L_0 = 2$, $L_1 = 1$ a term is the sum of the two preceding terms. That is, for $n \geq 2$,

$$L_n = L_{n-1} + L_{n-2} \quad 1.3)$$

According to this definition, the first few Lucas numbers are as follows:

$$L_0 = 2$$

$$L_1 = 1$$

$$L_2 = 3$$

$$L_3 = L_2 + L_1 = 3 + 1 = 4$$

$$L_4 = L_3 + L_2 = 4 + 3 = 7$$

$$L_5 = L_4 + L_3 = 7 + 4 = 11$$

$$L_6 = L_5 + L_4 = 11 + 7 = 18$$

⋮

Just as Fibonacci numbers, there is a Binet formula for Lucas numbers that serves to calculate the n . term directly. Given the golden ratio $\alpha = \frac{1+\sqrt{5}}{2}$ known from the Fibonacci formula and its conjugate $\beta = \frac{1-\sqrt{5}}{2}$, the Binet formula for Lucas numbers is in the form of $L_n = \alpha^n + \beta^n$.

There are many identities between the Fibonacci and Lucas number sequences. Some of the most fundamental ones are the following:

- Let n be a natural number, $L_n F_n = F_{2n}$ (Koshy, 2001).

Proof:

$$\begin{aligned}
 L_n F_n &= (\alpha^n + \beta^n) \left(\frac{\alpha^n - \beta^n}{\sqrt{5}} \right) \\
 &= \frac{(\alpha^n)^2 - (\beta^n)^2}{\sqrt{5}} \\
 &= \frac{\alpha^{2n} - \beta^{2n}}{\sqrt{5}} \\
 &= F_{2n}
 \end{aligned}$$

- For every natural number $n \geq 1$, $L_n = F_{n+1} + F_{n-1}$ is obtained.

Proof:

$$\begin{aligned}
 F_{n+1} + F_{n-1} &= \left(\frac{\alpha^{n+1} - \beta^{n+1}}{\sqrt{5}} \right) + \left(\frac{\alpha^{n-1} - \beta^{n-1}}{\sqrt{5}} \right) \\
 &= \frac{1}{\sqrt{5}} [(\alpha^{n+1} \alpha^{n-1}) - (\beta^{n+1} + \beta^{n-1})] \\
 &= \frac{1}{\sqrt{5}} [\alpha^n (\alpha + \alpha^{-1}) - \beta^n (\beta + \beta^{-1})] \\
 &= \frac{1}{\sqrt{5}} [\alpha^n \sqrt{5} - \beta^n \sqrt{5}] \\
 &= \frac{\sqrt{5}}{\sqrt{5}} (\alpha^n + \beta^n) \\
 &= \alpha^n + \beta^n = L_n
 \end{aligned}$$

Fibonacci Generalizations

Theoretical research on Fibonacci and Lucas sequences has shown that these sequences are special examples of a broader family of second-order linear recurrence sequences. Studies in this field generally focus on generalizing the structure of these sequences (Swamy, 1999). The most comprehensive and widely studied of these generalizations is the approach that preserves the second-order structure of the sequence and extends both the initial conditions and the coefficients in the recurrence relation to arbitrary integers. This general sequence is known as the Horadam Sequence in reference to the pioneering works of Horadam (Belbachir & Amine, 2018). It is denoted by (U_n) .

Let p and q be distinct integer coefficients, and a and b be arbitrary integer initial conditions. The Horadam sequence (U_n) is defined by a linear recurrence relation for $n > 1$. The first two terms of the sequence are $U_0 = a$ and $U_1 = b$.

$$U_n = pU_{n-1} + qU_{n-2}$$

Now let us obtain the Binet formula of the sequence.

$$U_n = A\alpha^n + B\beta^n$$

$$U_0 = A + B = a$$

$$U_1 = A\alpha + B\beta = b \text{ if the expression } B = a - A \text{ is substituted,}$$

$$A\alpha + (a - A)\beta = b$$

$$A\alpha + a\beta - A\beta = b$$

$$A(\alpha - \beta) + \alpha\beta = b$$

$$A = \frac{b - \alpha\beta}{\alpha - \beta} \text{ and } B = \frac{a\alpha - b}{\alpha - \beta}$$

If we substitute the values of A and B we found into equation (1.4), we obtain the following Binet formula.

$$U_n = \left(\frac{b - \alpha\beta}{\alpha - \beta} \right) \alpha^n + \left(\frac{a\alpha - b}{\alpha - \beta} \right) \beta^n$$

Now let us obtain the generating function of the sequence.

$$h(x) = \sum_{n=0}^{\infty} U_n x^n \rightarrow h(x) = U_0 + U_1 x + U_2 x^2 + \cdots + U_n x^n + \cdots$$

$$h(x) = a + bx + \sum_{n=2}^{\infty} U_n x^n$$

$$h(x) = a + bx + px \sum_{n=2}^{\infty} (pU_{n-1} + qU_{n-2}) x^{n-2}$$

$$h(x) = a + bx + px \sum_{n=2}^{\infty} U_{n-1} x^{n-1} + qx^2 \sum_{n=2}^{\infty} U_{n-2} x^{n-2}$$

$$h(x) = a + bx + px(h(x) - a) + qx^2 h(x)$$

$$h(x) = a + bx + pxH(x) - apx + qx^2 h(x)$$

$$h(x) - pxh(x) - qx^2 h(x) = a + bx + pax$$

$$h(x)(1 - px - qx^2) = a + x(b - pa)$$

$$h(x) = \frac{a + x(b - pa)}{1 - px - qx^2}$$

if a and b are substituted;

$$h(x) = \frac{U_0 + x(U_1 - pU_0)}{1 - px - qx^2}$$

This definition unites many important sequences in number theory under a single roof with different integers assigned to the values of p, q, a, b . This unified approach allows for the investigation of structures such as Binet formulas and generating functions of different sequences (Belbachir & Amine, 2018; Koshy, 2001).

Table 1. Special number sequences

p	q	a	b	Notation	Name of the sequence
1	1	0	1	F_n	Fibonacci Sequence
1	1	2	1	L_n	Lucas Sequence
2	1	0	1	P_n	Pell Sequence
2	1	2	2	p_n	Pell-Lucas Sequence
1	2	0	1	J_n	Jakobsthal Sequence
1	2	2	1	j_n	Jakobsthal-Lucas Sequence

Incomplete Fibonacci and Lucas Numbers

Fibonacci and Lucas numbers are expressed through combinatorial sums (Koshy, 2001).

$$F_n = \sum_{i=0}^{\lfloor \frac{n-1}{2} \rfloor} \binom{n-1-i}{i}$$

$$L_n = \sum_{i=0}^{\lfloor \frac{n}{2} \rfloor} \frac{n}{n-i} \binom{n-i}{i}$$

Incomplete Fibonacci Numbers

Many generalizations have been made in the literature for these special number sequences. One of these, the Incomplete Fibonacci numbers, is defined as follows (Filipponi, 1996);

$$F_n(k) = \sum_{j=0}^k \binom{n-1-j}{j}, \quad 0 \leq k \leq \tilde{n}; \quad \tilde{n} = \left\lfloor \frac{n-1}{2} \right\rfloor \quad (2.1)$$

The numbers $F_n(k)$ for a few values of n and the corresponding values of k are shown in Table 2.

Some special cases obtained from equation (2.1) are as follows.

- Let $n \geq 1$ and n be a natural number, $F_n(\tilde{n}) = F_n$
- For $n \geq 3$, $F_n(\tilde{n} - 1) = \begin{cases} F_n - \frac{n}{2}, & n \text{ is even} \\ F_n - 1, & n \text{ is odd} \end{cases}$
- For $n \geq 1$, $F_n(0) = 1$

Table 2. $F_n(k), 1 \leq n \leq 8$					
k	0	1	2	3	...
n					
1	1				
2	1				
3	1	2			
4	1	3			
5	1	4	5		
6	1	5	8		
7	1	6	12	13	
8	1	7	17	21	
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\ddots$

Proof: Let us give the proof of the 2nd property.

$$\sum_{j=0}^{\tilde{n}} \binom{n-1-j}{j} - \binom{n-1-\tilde{n}}{\tilde{n}}$$

$$= F_n - \binom{n-1-\tilde{n}}{\tilde{n}}$$

$$\text{if } \rightarrow n = 2k \quad (\tilde{n} = k-1)$$

$$= F_n - \binom{2k-1-(k-1)}{k-1} = F_n - \binom{k}{k-1} = F_n - \frac{n}{2}$$

$$\text{if } \rightarrow n = 2k+1 \quad (\tilde{n} = k)$$

$$= F_n - \binom{2k+1-1-k}{k} = F_n - \binom{k}{k} = F_n - 1$$

Incomplete Lucas Numbers

$$L_n(k) = \sum_{j=0}^k \frac{n}{n-j} \binom{n-j}{j} \quad 0 \leq k \leq \tilde{n}; \tilde{n} = \left\lfloor \frac{n}{2} \right\rfloor \quad (2.2)$$

The numbers $L_n(k)$ for a few values of n and the corresponding values of k are shown in Table 3 (Filipponi, 1996).

Some special cases obtained from equation (2.2) are given below.

- For $n \geq 1$, $L_n(0) = 1$
- For $n \geq 2$, $L_n(1) = n + 1$
- For $n \geq 4$, $L_n(2) = \frac{n^2-n+2}{2}$

Table 3. $L_n(k), 1 \leq n \leq 8$					
k	0	1	2	3	...
n					
1	1				
2	1	3			
3	1	4			
4	1	5	7		
5	1	6	11		
6	1	7	16	18	
7	1	8	22	29	
8	1	9	29	45	
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\ddots$

Proof: Let us give the proof of the 3th property.

$$\begin{aligned}
 L_n(2) &= \sum_{j=0}^2 \frac{n}{n-j} \binom{n-j}{j} \\
 &= \frac{n}{n} \binom{n}{0} + \frac{n}{n-1} \binom{n-1}{1} + \frac{n}{n-2} \binom{n-2}{2} \\
 &= 1 + n + \frac{n}{n-2} \frac{(n-2)(n-3)}{2} = \frac{n^2 - n + 2}{2}
 \end{aligned}$$

Incomplete Fibonacci and Lucas Numbers with Arithmetic Indices

Waring Formula

The Waring formula is a fundamental method used in obtaining the explicit form of linear recurrences. This formula allows expressing the general term of the sequence directly, without resorting to the recursive definition, with the help of the roots of the characteristic equation. In particular, it can be considered as a generalized form of the known Binet formula for Fibonacci and Lucas-like sequences. The Waring formula for Fibonacci and Lucas numbers is as follows (Swamy, 1999; Ramirez, 2013).

$$\frac{X^n - Y^n}{X - Y} = \sum_{k=0}^{\lfloor \frac{n-1}{2} \rfloor} (-1)^k \binom{n-k-1}{k} (XY)^k (X+Y)^{n-2k-1} \quad (3.1)$$

$$X^n + Y^n = \sum_{k=0}^{\lfloor \frac{n}{2} \rfloor} (-1)^k \frac{n}{n-k} \binom{n-k}{k} (XY)^k (X+Y)^{n-2k} \quad (3.2)$$

Incomplete Fibonacci Number Sequence with Arithmetic Indices

The Fibonacci number sequence with arithmetic indices is defined as follows (Kılıç & Stanica, 2009)

$$F_{rn} = L_r F_{r(n-1)} - (-1)^r F_{r(n-2)} \quad (3.3)$$

The Binet formula of the Fibonacci number sequence with arithmetic indices is obtained as follows.

$$F_{rn} = \frac{\alpha^{rn} - \beta^{rn}}{\alpha - \beta}$$

The explicit formula of the relation number (3.3) is obtained using the Waring Formula (3.1). This approach allowed for the systematic derivation of the explicit formula of the sequence. If the expressions

$X = \alpha^r, Y = \beta^r$ are substituted,

$$X + Y = \alpha^r + \beta^r = L_r$$

$$XY = \alpha^r \beta^r = (-1)^r$$

$$\frac{\alpha^{rn} - \beta^{rn}}{\alpha^r - \beta^r} = \sum_{k=0}^{\lfloor \frac{n-1}{2} \rfloor} (-1)^k \binom{n-k-1}{k} ((-1)^r)^k (L_r)^{n-2k-1}$$

$$\frac{F_{rn}}{F_r} = \sum_{k=0}^{\lfloor \frac{n-1}{2} \rfloor} (-1)^{k(r+1)} \binom{n-k-1}{k} (L_r)^{n-2k-1}$$

$$F_{rn} = F_r \sum_{k=0}^{\lfloor \frac{n-1}{2} \rfloor} (-1)^{k(r+1)} \binom{n-k-1}{k} (L_r)^{n-2k-1}$$

$$F_{rn}^l = F_r \sum_{k=0}^l (-1)^{k(r+1)} \binom{n-k-1}{k} (L_r)^{n-2k-1} \quad (3.4)$$

Table 4. $F_{rn}^l, r = 3, 1 \leq n \leq 8$

n	1	0	1	2	3	...
1		2				
2		8				
3		32	34			
4		128	144			
5		512	608	610		
6		2048	2560	2584		
7		8192	10752	10944		
8		32768	45056	46336	46368	
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\ddots$

Some special cases can be obtained for (3.4).

- Let $n \geq 1$ and n be a natural number, $F_{rn}^{\lfloor \frac{n-1}{2} \rfloor} = F_{rn}$
- For $n \geq 3$, $F_{rn}^1 = F_r L_r^{n-1} + F_r (n-2)(-1)^{r+1} L_r^{n-3}$
- For $n \geq 5$, $F_{rn}^2 = F_r L_r^{n-1} + F_r (n-2)(-1)^{r+1} L_r^{n-3} + F_r \frac{(n-3)(n-4)}{2} L_r^{n-5}$
- For $n \geq 3$, $F_{rn}^{\lfloor \frac{n-3}{2} \rfloor} = \begin{cases} F_{rn} - F_r (-1)^{\frac{n-1}{2}(r+1)}, n \text{ is odd} \\ F_{rn} - F_r \frac{n}{2} L_r (-1)^{\frac{n-2}{2}(r+1)}, n \text{ is even} \end{cases}$

Incomplete Lucas Numbers Sequence with Arithmetic Indices

The Lucas number sequence with arithmetic indices is defined as follows.

$$L_{rn} = L_r L_{r(n-1)} - (-1)^r L_{r(n-2)} \quad (3.5)$$

The Binet formula of the Lucas number sequence with arithmetic indices is obtained as follows.

$$L_{rn} = \alpha^{rn} + \beta^{rn}$$

The explicit formula of the relation number (3.5) is obtained using the Waring Formula (3.2). This approach allowed for the systematic derivation of the explicit formula of the sequence.

If the expressions $X = \alpha^r, Y = \beta^r$ are substituted,

$$X + Y = \alpha^r + \beta^r = L_r$$

$$XY = \alpha^r \beta^r = (-1)^r$$

$$\begin{aligned} \alpha^{rn} + \beta^{rn} &= \sum_{k=0}^{\lfloor \frac{n}{2} \rfloor} (-1)^k \frac{n}{n-k} \binom{n-k}{k} ((-1)^r)^k (L_r)^{n-2k} \\ L_{rn} &= \sum_{k=0}^{\lfloor \frac{n}{2} \rfloor} (-1)^{k(r+1)} \frac{n}{n-k} \binom{n-k}{k} (L_r)^{n-2k} \\ L_{rn}^l &= \sum_{k=0}^l (-1)^{k(r+1)} \frac{n}{n-k} \binom{n-k}{k} (L_r)^{n-2k} \end{aligned} \quad (3.6)$$

Some special cases can be obtained for (3.6).

- Let $n \geq 1$ and n be a natural number, $L_{rn}^{\lfloor \frac{n-1}{2} \rfloor} = L_{rn}$
- For $n \geq 1$, $L_{rn}^0 = (L_r)^n$
- For $n \geq 2$, $L_{rn}^1 = L_r^n + n(-1)^{r+1} (L_r)^{n-2}$
- For $n \geq 4$, $L_{rn}^2 = (L_r)^n + n(-1)^{r+1} (L_r)^{n-2} + \frac{n(n-3)}{2} (L_r)^{n-4}$

Table 5. $L_{rn}^l, r = 5, 1 \leq n \leq$

l	0	1	2	3	...
n					
1	11				
2	121	123			
3	1331	1364			
4	14641	15125	15127		
5	161051	167706	167761		
6	1771561	1859407	1860496	1860498	
7	19487171	20614528	20633162	20633239	
8	214358881	228531369	228824189	228826125	
⋮	⋮	⋮	⋮	⋮	⋮

$$\text{For } n \geq 3, L_{rn}^{\lfloor \frac{n-3}{2} \rfloor} = \begin{cases} L_{rn} - n(-1)^{\frac{n-1}{2}(r+1)} L_r, n \text{ is odd} \\ L_{rn} - \frac{n^2}{4}(-1)^{\left(\frac{n}{2}-1\right)(r+1)} (L_r)^2 + 2(-1)^{\frac{n}{2}(r+1)}, n \text{ is even} \end{cases}$$

Method

In this study, various analytical and algebraic methods were employed to investigate the properties of Fibonacci and Lucas number sequence38s and to generalize these. The Binet formula, derived from the roots of the characteristic equation α and β was utilized to obtain the general terms of the fundamental sequences, the identities among them, and their generating functions. Furthermore, utilizing A.F. Horadam's approach to generalize second-order linear recurrence sequences, the generating functions of various sequences (e.g., Pell, Jacobsthal) were examined within a single unified framework (Belbachir & Amine, 2018; Koshy, 2001). In order to obtain the explicit formulas for the Incomplete Fibonacci and Lucas numbers, as well as their arithmetic-indexed versions discussed in the later stages of the study, the Waring formula—a highly effective tool for solving linear recurrences—was employed rather than relying on recursive definitions. The validity of the relevant theorems and identities was demonstrated through step-by-step proofs using algebraic manipulations and combinatorial sums.

Results and Discussion

As a result of this study, new analytical (closed-form) formulas were obtained for the arithmetic-indexed versions of the Incomplete Fibonacci and Lucas sequences. Through the effective utilization of Waring's formula, the general terms of the sequences could be computed directly, eliminating the computational burden introduced by recursive calculations. It has been algebraically proven that these general equations seamlessly reduce to the classical Fibonacci and Lucas sequences under special conditions. Moreover, by employing A.F. Horadam's approach, it was demonstrated that distinct sequences, such as Pell and Jacobsthal, can be unified under a single mathematical framework. It is anticipated that this developed analytical framework and the novel identities will establish a robust foundation for future research on higher-order number sequences.

Conclusion

In this study, new analytical formulas for the arithmetic-indexed versions of Incomplete Fibonacci and Lucas sequences were successfully obtained using Waring's formula. These results enabled the direct calculation of the general terms of the sequences without the need for recursive computations, unifying various number sequences under a common framework. It is expected that these newly introduced identities will lay a significant groundwork for future research on higher-order sequences.

Recommendations

For future research, it is recommended to extend the method developed in this study to third-order or higher-order number sequences (e.g., the Tribonacci sequence).

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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Author(s) Information	
Ebru Sena Kurt Konya Technical University Graduate Education Institute Mathematics Department, Konya, Türkiye ORCID iD: https://orcid.org/0009-0005-7164-2021 *Contact e-mail: ebrusenakurt94@gmail.com	Nurettin Irmak Konya Technical University Engineering and Natural Science Faculty, Department of Engineering Basic Science Konya, Türkiye ORCID iD: https://orcid.org/0000-0003-0409-4342
*Corresponding author(s) contact email	

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A Study of Juglone in Georgian Walnuts (Juglon regia) by Chromato-Mass Spectrometry

Miranda Paksadze

Batumi Shota Rustaveli State University

Maia Vanidze

Batumi Shota Rustaveli State University

Jeiran Putkaradze

Batumi Shota Rustaveli State University

Aleko Kalandia

Batumi Shota Rustaveli State University

Maia Kharadze

Batumi Shota Rustaveli State University

Abstract: The study concerns the identification and quantification of the biologically active naphthoquinone, juglone (5-hydroxy-1,4-naphthoquinone), in the walnut (*Juglans regia*), a species widespread in Georgia, using an ultra-high-performance liquid chromatograph. The relevance of this research lies in the need to valorize agro-food waste and adopt zero-waste principles, which constitute an important aspect of the circular economy. Walnut peel obtained during processing is considered a potentially rich source of juglone, which is used for its antimicrobial, anti-inflammatory, antifungal, and other effects. Mass spectrometric analysis identified juglone with a characteristic molecular mass (m/z 173 [M-H]). The effects of different extraction methods (ultrasound, classical, high pressure/temperature, hot extraction with reflux, lyophilization) and solvent on the yield of the target compound were compared. Quantitative data showed that the maximum juglone content was observed in the ethyl acetate extract of lyophilized walnut skin, exceeding that of the ethyl acetate extract of the sample dried at 40°C and of the raw skin. Relatively low concentrations were detected in the ultrasonic and classical extraction using 50% ethanol, while the minimum amount was found in the condensate formed during lyophilization. The results obtained indicate that walnut peel represents a promising raw material for juglone, and that lyophilization combined with ethyl acetate extraction can be considered the optimal technological approach for maximizing the extraction of the target compound. This study provides a basis for the targeted utilization of walnut agro-waste and for the optimization of technological processes aimed at obtaining bioactive compounds.

Keywords: Juglone, Mass-spectrometry, Zero-waste.

Introduction

In recent decades, environmental pollution has emerged as one of the most pressing challenges worldwide. The growing number of landfills and the accumulation of untreated waste pose significant threats to the environment and to all living organisms, contributing to climate change and the contamination of water, soil, and air. For instance, approximately 146 million tons of waste are disposed of in landfills annually in the United States. The food industry represents a particularly serious concern, as food waste constitutes one of the largest sources of

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pollution, accounting for about 24% of the total (World Economic Forum, 2023). Accordingly, increasing attention has been directed toward the zero-waste concept, first introduced in 1970 by chemist Paul Palmer, who demonstrated the potential for reusing chemicals discarded by emerging technology companies in Silicon Valley. The zero-waste approach has continued to evolve and has gained greater relevance in recent years, as it represents one of the key principles of the circular economy. In line with United Nations General Assembly Resolution 77/161, the Zero Waste Initiative has been endorsed by more than one hundred countries, including Georgia (Ministry of Environmental Protection and Agriculture of Georgia [MEPA], 2023). Thus, Georgia is actively aligning with global efforts to address the so-called “triple crisis.” Nevertheless, waste recycling remains a complex challenge, particularly in our country. This is largely due to the novelty of the field, the limited availability of literature on specific facilities, recycling technologies, and methodologies, as well as a shortage of qualified professionals, all of which contribute to the overall complexity of the issue. In this context, our study focuses on plant-based biomass, specifically walnut (*Juglans regia*), which is often considered “waste” after food processing. Typically, these residues are discarded or incinerated, yet they hold considerable potential for various applications.

Walnut fruits, especially at the milk-ripe stage, are widely used for the production of preserves and other food products, generating substantial by-products and industrial residues. Plant-based biomass and the bioactive compounds derived from it are valuable resources for pharmaceuticals, sorbents, and other applications. Notably, naphthoquinones, such as juglone (5-hydroxy-1,4-naphthoquinone), are present in walnuts, leaves, roots, and bark (Kavtaradze, 2005). Walnut bark extracts are utilized as pigments in cosmetics, textiles, and the food industry due to their yellow coloration, which turns reddish-brown upon oxidation. Additionally, these extracts exhibit therapeutic properties, including antimicrobial, antifungal, and anticancer effects, and are applied in the treatment of skin disorders and infections. Therefore, the potential pharmaceutical application of walnut biomass is of considerable scientific and economic interest.

Members of the walnut family comprise evergreen, semi-evergreen, and deciduous plants, encompassing approximately 60 species that are predominantly distributed in tropical and subtropical regions (Bai et al., 2024). Archaeological evidence suggests that the collection and use of walnuts originated in the Mediterranean region more than 7,000 years ago. The most widely distributed species include *Juglans regia* (English or Persian walnut), *Juglans nigra* (black walnut), *Juglans sieboldiana* (Japanese walnut), and *Juglans cinerea* (white walnut, also known as butternut) (Suzuki & Taseer, 2019). A walnut consists of several structural components. The fruit is initially enclosed in a green outer layer (husk or hull), which degrades and separates from the nut during the ripening process. Beneath this layer lies a hard shell, which is mechanically removed to obtain the edible portion. The seed itself is further covered by a thin skin. Walnut shells have traditionally been utilized for various purposes, including as a fuel source for heating, as an abrasive material for cleaning, and as a biofilter in the treatment of wastewater and oilfield effluents. In addition, they exhibit antioxidant and antimicrobial properties (Chamorro et al., 2022).

In recent years, the beneficial properties of walnuts have been widely discussed, and scientific interest in this raw material has increased due to its recognized value. The positive effects of walnuts are largely determined by their chemical composition. They are characterized by a low glycemic index and represent an important source of polyphenols, polyunsaturated fatty acids, and essential biogenic amino acids. In addition, walnuts possess high nutritional value (Sánchez-Morgado et al., 2013).



Figure 1. *Juglans regia*



Figure 2. *Juglans regia*, green husk

Leaves of walnut (*Juglans regia*) exhibit protective properties against various diseases, primarily due to their antioxidant activity. For example, compounds such as ascorbic acid, as well as organic acids including citric and malic acids, demonstrate antioxidant capacity through their ability to form chelate complexes with metal ions. Essential fatty acids, tocopherols, phytosterols, proteins, minerals, vitamins, and phenolic compounds collectively contribute to the health-promoting properties of walnuts. Recent studies indicate that walnuts serve as a source of natural antioxidants and may help prevent diseases associated with oxidative stress (Santos et al., 2013).

Juglone

Juglone has been shown to suppress the growth of various cancer cells, including those of the stomach, pancreas, and lungs, as well as certain human papillomavirus (HPV)-infected cells, such as HeLa and MIA PaCa-2, at concentrations ranging from 10 to 100 μM . The presence of juglone also gives walnuts allelopathic properties, making this compound a promising natural herbicide, particularly for weed control (Kavtaradze, 2005). In addition to plants, juglone exerts toxic effects on fungi, protists, and certain animals. Its antifungal activity has been compared with that of synthetic fungicides, such as clotrimazole and selenium sulfide, demonstrating moderate efficacy (Mominul Islam & Widhalm, 2020). Juglone is a natural toxin with multiple bioactivities, including the capacity to induce apoptosis, which varies depending on the cell type. Despite extensive research, the precise mechanisms underlying these effects remain unclear. Its cytotoxic and genotoxic actions include induction of oxidative stress, membrane damage, apoptosis, and necrotic cell death (Suzuki & Taseer, 2019). Cytotoxicity is primarily mediated through two mechanisms: redox cycling and interaction with glutathione. Recent studies have reported that juglone induces cell death in human lung carcinoma (A549), colorectal carcinoma (HT-29), and human keratinocyte (HaCaT) cell lines (Xu et al., 2010).

Walnuts contain various phenolic compounds, including flavonoids, terpenoids, and naphthoquinones. Juglone belongs to the naphthoquinone group, a class of aromatic organic compounds characterized by a phenyl moiety. Other widely distributed naphthoquinones include lawsone, plumbagin, and lapachol. Quinones are cyclic diketones, and naphthoquinones exist as three isomers: naphthoquinone, 0-amphi-naphthoquinone (Strugstad & Despotovski, 2012). Juglone typically appears as orange, needle-like crystals that are slightly soluble in water but readily soluble in organic solvents. It is primarily derived from naphthalene derivatives and is more effective when extracted from compounds containing functional groups in the 1,5-position (Kavtaradze, 2005). Juglone is particularly abundant in walnut husks and roots, with its concentration varying seasonally. In 1943, it was observed that juglone exists in the inner bark of walnut roots in a non-toxic form, α -hydrojuglone, which oxidizes to juglone upon exposure to air. Later studies identified that in walnut wood, juglone is stored as 1,4,5-trihydroxynaphthalene-5-glucoside, which, due to its lability, can easily degrade into glucose and juglone (Strugstad & Despotovski, 2012).

Recent innovative extraction methods have improved the stability and applicability of juglone for industrial and medical purposes. A study conducted in 2025 demonstrated high efficiency using a “green” approach that combines mechanochemistry with aqueous two-phase extraction to obtain high-purity juglone from *Juglans mandshurica* (Manchurian walnut) (Wei et al., 2025). Nano-encapsulation has been successfully employed to incorporate juglone into PLGA nanoparticles, achieving up to 90% efficacy. This method enhances water solubility and increases apoptotic activity in cancer cells (Yilmaz et al., 2025). Furthermore, cyclodextrin inclusion complexes have been shown to improve the thermal and pH stability of juglone, effectively doubling its antimicrobial potential against *Escherichia coli* and *Staphylococcus aureus* (Arayıcı et al., 2024).

Aim and Methods

Materials and Methods: Sample Preparation and Extraction

The aim of our study was to investigate the content of juglone in Georgian walnuts at the milk ripening stage using ultra-high-performance liquid chromatography coupled with a mass spectrometric detector (UPLC-MS-PDA), performing a comparative analysis based on solvents and extraction conditions. Initially, samples were prepared from lyophilized and fresh walnut skins, as well as skins dried at 40°C. Solvents included water, ethyl acetate, and ethanol at concentrations of 50% and 96%. Both ultrasonic probe-assisted and conventional extraction methods were employed, including ultrasonic bath extraction with vacuum filtration, hot extraction under reflux, and high-pressure, high-temperature extraction.

For the extraction procedures, the green husks were removed from fresh walnuts, and 50 g of skins were chopped. In one set of experiments, 200 mL of 50% ethanol was added to each portion, followed by homogenization for 1 min. The samples were then incubated in an ultrasonic bath for 15 min and filtered under vacuum. In the second set, an ultrasonic probe was used in place of the homogenizer. For the third set, hot extraction under reflux was applied, while the fourth set utilized high-pressure, high-temperature extraction. For classical extraction, dried walnut skins at 40°C were treated with 96% ethanol for 18 h, maintaining a solid-to-liquid ratio of 1:6. At the first stage, 7 g of fresh skins were mixed with 42 mL of 96% ethanol. In the subsequent stages, 3.64 g of skins were mixed with 21.84 mL of ethanol, with each extraction step lasting 1 min at 70°C. All extracts were filtered through paper filters. For ethyl acetate extraction, 1 g of dried, fresh, or lyophilized skins was mixed with 10 mL of ethyl acetate, homogenized, incubated in an ultrasonic bath, and filtered under vacuum. Prior to chromatography, all extracts were filtered through “Waters Acrodisc LC PVDF Filter 13 mm, 0.45 µm.”

Results and Discussion

Identification of Compounds by Ultra-High-Performance Liquid Chromatography with a Mass Spectrometric Detector (UPLC-MS-PDA)

Analysis was performed using a Waters ACQUITY UPLC system coupled with a QDa detector (ESI). The column was ACQUITY BEH C18 (2.1 × 100 mm, 1.7 µm). Mobile phase A consisted of 0.1% formic acid in water, and mobile phase B was acetonitrile. Gradient elution was applied as follows: 0–2.0 min, 5% B; 2.0–8.0 min, 20% B; 8.0–10.0 min, 35% B; 10.0–11.0 min, 95% B; 12.0–15.0 min, 5% B. The flow rate was 0.3 mL/min, injection volume 2 µL, and column temperature 40°C. MS conditions were as follows: Ionization, ESI+; Capillary voltage, 0.8 kV; Cone voltage, 15 V; Source temperature, 120°C; Desolvation temperature, 500°C; Mode, SIR; Scan range, m/z 100–1000. Calibration was performed with 5–7 points (0.1–100 µg/mL), $R^2 \geq 0.995$. **Statistical Analysis:** Results are expressed as mean ± SEM. Student’s t-test was used to assess statistical significance between groups. A p-value < 0.05 was considered statistically significant (Putkaradze, et al., 2026).

Table 1. Tentative UPLC–MS profiling of walnut husks

No	RT(min)	m/z	Fragment ions (MS/MS)	Tentative identification	Class
1	0.75	133		Malic acid	Organic acid
2	6.648	173.03	145	Juglone	Naphthoquinone
3	8.372	446.91	301	Quercetin-3-O-glucoside	Flavanoid
4	8.795	447.17		Quercetin-galactoside	Flavanoid

Table 2. Juglone extraction efficiency across solvents and methods

Sample Name	Extraction Method	Solvent	Result mg/g
Green walnut husk	Ultrasound-assisted extraction (probe)	50% Ethanol	6.96
Green walnut husk	US extraction	50% Ethanol	20.81
Green walnut husk	High-pressure and high-temperature extraction	50% Ethanol	18.15
Green walnut husk	Hot extraction with reflux	50% Ethanol	17.60
Green walnut husk dried dried at 40 °C	classical extraction	96% Ethanol and water	9.89
Green walnut husk	Classical extraction	Ethyl acetate	32.81
Lyophilized Green walnut husk dried	Classical extraction	Ethyl acetate	38.80
Green walnut husk dried dried at 40 °C	Classical extraction	Ethyl acetate	35.27
Condensate formed during lyophilization			2.68

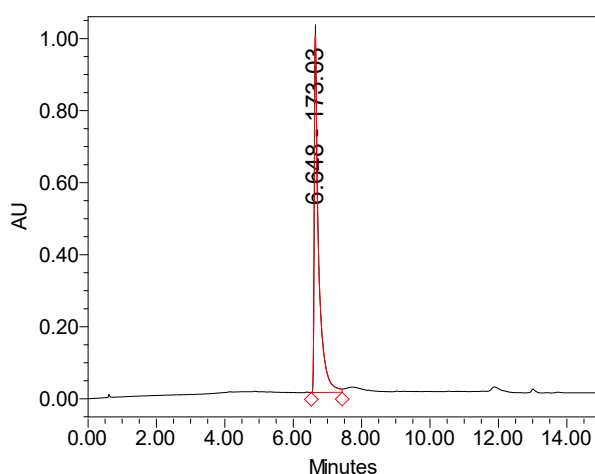


Figure 3. Juglone (5-hydroxy-1,4-naphthoquinone)

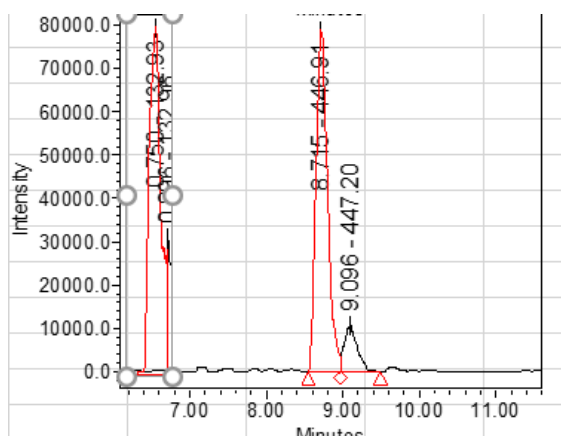


Figure 4. Phenolic compounds in walnut green husk

In addition to juglone (RT 6.648 min, m/z $[M-H]^-$ 173.03), UPLC–ESI–MS analysis of the walnut extracts identified several other compounds, including malic acid (RT 0.75 min, m/z $[M-H]^-$ 133), the flavonoid quercetin-3-O-glucoside (RT 8.372 min, m/z $[M-H]^-$ 446.91), and quercetin-galactoside (RT 8.795 min, m/z $[M-H]^-$ 447.17) (Table 1). Classical methods for isolating juglone from walnut husks involve grinding the husks, drying them at 30–35 °C, and extracting with 70% ethanol, which yields a solution containing approximately 1.45 mg/mL of juglone. Using ethyl acetate for extraction increases the concentration to 2.05 mg/mL. Furthermore, lyophilization of the starting material followed by ethyl acetate extraction enhances the yield to 3.25 mg/mL, representing an approximately twofold increase. Notably, during the drying process, juglone crystals also condense, resulting in about 2.0 g of juglone obtained from 1 kg of husks (Table 2).

Conclusion

Ultra-high-performance liquid chromatography coupled with mass spectrometric detection (UHPLC–MS) was used to identify the naphthoquinone compound juglone (5-hydroxy-1,4-naphthoquinone; m/z 173 $[M-H]^-$), as well as malic acid and several phenolic constituents, including quercetin glycosides such as quercetin-3-O-glucoside and quercetin-galactoside. A comparative analysis of the samples was conducted, taking into account the extraction conditions and the solvents used. The results showed that the highest yield of bioactive compounds was obtained with ethyl acetate, particularly when applied to lyophilized walnut husks. Lower, yet still substantial, extraction efficiency was observed for samples processed at 40 °C and for extracts prepared from raw material. When ethanol was employed as the solvent, the most efficient extraction was achieved under elevated temperature and pressure conditions, followed by ultrasonic probe-assisted extraction. These findings highlight the importance of optimizing the extraction method, temperature, and solvent type to maximize the recovery of bioactive compounds.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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Author(s) Information

Miranda Paksadze

Batumi Shota Rustaveli University
Georgia. Batumi. Rustaveli/Ninoshvili 32/35, Batumi,
Georgia
ORCID iD: <https://orcid.org/0009-0000-4395-0362>
*Contact e-mail: miranda.paksadze@bsu.edu.ge

Maia Vanidze

Batumi Shota Rustaveli University
Georgia. Batumi. Rustaveli/Ninoshvili 32/35, Batumi,
Georgia
ORCID iD: <https://orcid.org/0000-0003-0807-0735>

Jeiran Putkaradze

Batumi Shota Rustaveli University
Georgia. Batumi. Rustaveli/Ninoshvili 32/35, Batumi,
Georgia
ORCID iD: <https://orcid.org/0009-0006-2566-6038>

Aleko Kalandia

Batumi Shota Rustaveli University
Georgia. Batumi. Rustaveli/Ninoshvili 32/35, Batumi,
Georgia
ORCID iD: <https://orcid.org/0000-0001-9570-9263>

Maia Kharadze

Batumi Shota Rustaveli University
Georgia. Batumi. Rustaveli/Ninoshvili 32/35, Batumi,
Georgia
ORCID iD: <https://orcid.org/0000-0001-6754-616>

*Corresponding author(s) contact email

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Experimental Investigation on Tensile Property of Plain-Woven Glass/Polyester Composite

Yusuf Sahin

OSTIM Technical University

Halil Ridvan Oz

OSTIM Technical University

Ceren Cetinkaya

OSTIM Technical University

Abstract: Due to their cost efficiency and superior mechanical properties, Glass Fiber-Reinforced Polymer (GFRP) composites are attracting increasing attention across various industrial sectors, including aeronautics, automotive, marine, chemical, and sporting goods industries. This study investigates the tensile behavior of plain-woven GFRP laminates through experimental characterization. The laminates were fabricated using unsaturated polyester resin via the Vacuum Bagging (VB) technique, employing a single stacking sequence of $[0/90^\circ]_s$. Uniaxial tensile tests were conducted in accordance with ASTM standards. In addition, Hooke's law equations for two-dimensional composites were applied to determine the local stresses and strains in each ply. The results demonstrated a high sensitivity of tensile properties to fiber orientation. The $[0/90^\circ]_s$ laminates tested at 0° orientation exhibited the highest tensile strength of 317 MPa and a Young's modulus of 18.94 GPa, while specimens tested at 30° orientation showed significantly reduced performance, yielding a tensile strength of 114 MPa and a Young's modulus of 10.6 GPa. Furthermore, the maximum and minimum local stresses (σ_1) in the 1st and 2nd plies were approximately 4.085×10^4 Pa and -1.63×10^4 Pa, respectively, for the glass/epoxy lamina, while the corresponding maximum and minimum strains (ϵ_1) in the 1st and 2nd plies were approximately 9.9×10^{-7} and 7.785×10^{-8} , respectively.

Keywords: GFRP; Polyester resin, Vacuum bagging, Tensile properties, Young's modulus, Fiber orientation, Plain-woven fabric, Laminate

Introduction

Composite materials are advanced multiphase systems consisting of continuous fibers or fabrics embedded within a polymer matrix. By combining two or more constituents, these materials overcome the limitations of their individual components, offering high specific stiffness/stiffness, higher corrosion resistance, design flexibility and lightweight properties. As a result of these properties, Glass Fiber Reinforced Polymers (GFRP) and Carbon Fiber Reinforced Polymers (CFRP) have become primary materials in the automotive, aerospace, and marine sectors (Zhang & Xu, 2022; Sarfnaz et al., 2021; Mallick et al., 2020). While carbon fibers offer superior stiffness and strength, but very brittle and costly. Due to cost-efficiency alongside mechanical performance, especially for impact behavior, glass fibers are often preferred in practical applications, such as wind turbine blades (Steigmann et al. 2016; Mishnaevsky et al. 2017). The mechanical performance of GFRP is significantly influenced by fiber loading and volume fraction (Kumar & Singh, 2021). While unidirectional (UD) composites provide exceptional properties along the fiber axis, textile (woven) composites have gained prominence in aerospace for their improved toughness, ease of handling, and near-net-shape manufacturing

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capabilities. However, the interlaced architecture of warp and weft yarns introduces complex stress distributions, making analytical modeling challenging (Selek & Sahin, 2023; Uzey et al. 2024).

Recent literature highlights the sensitivity of GFRP to external factors. Some researches on GFRP showed that hygrothermal effects, alkaline environments can reduce tensile strength by over 60%, a degradation often accelerated with high temperatures or sustained mechanical loads (Bazli et al., 2019, Bazli et al., 2026; Tefera et al., 2022; Zhu et al., 2022; Jin et al., 2020). Furthermore, GFRP exhibits rate-dependent behavior; Ou et al. (2016) noted a nearly 50% increase in tensile strength under high strain rates, though Young's modulus remains more sensitive to temperature than loading speed. Naito (2022) studied the static and fatigue tensile properties of carbon/glass hybrid fiber-reinforced epoxy composites. Explores the hybridization of PAN-based carbon (IMS60) and E-glass fibers. Static loading results showed linear stress-strain behavior for most hybrids, but specific layups ([E-glass/IMS60]) displayed jagged failure traces, indicating progressive internal damage. Huang et al. (2025) studied the experimental investigation of static strength in CFRP and Aluminium Lugs subjected to uniaxial tensile loading. This study compares twill woven CFRP lugs with conventional aluminum (L-Al). Experimental results show that Quasi-Isotropic layups can surpass aluminum in load-bearing capacity (450-550 MPa), while "soft" layups exhibit matrix cracking near bore holes that mimics metallic stress relief.

Lopresto et al. (2024) showed that mechanical characterisation of basalt fibre reinforced plastic: A comparison with glass-fibre reinforced composite (BFRP) under the same conditions. It is proved that BFRP has 25% higher impact and tensile strength than GFRP under the same conditions. Şahin and Selek (2025) showed that BFRP strength drops sharply when the load applied at 45° to the fiber direction, highlighting high anisotropy, in terms of fiber orientation. Dorigato and Pegoretti (2025) concluded that the tensile results had superior for BFRP before the first ply failure (FPF) compared to E-glass. Biswas et al. (2011) experimentally investigated that effect of fiber orientations on mechanical behaviors of glass fiber/epoxy composites. It is found that the 30° fiber orientation composites showed that superior microhardness compare with other fiber orientations irrespective of fiber loading. Similar studies on the effect of fiber orientation on the mechanical behavior are conducted at various composites (Kaw, 2006; Şahin, 2022, 2024; Ozsoy, 2015; Vinay et al., 2022), most of them reported the conflicting results, which are related to performance of tensile strengths, especially woven fabric reinforced composite in terms of bi-directional (warp or fill) testing conditions.

In the present study, therefore, GFRP plates were manufactured using a VB technique with an polymeric resin. Uniaxial tensile tests were conducted to determine the elastic modulus and ultimate tensile strength of five-layer plain-woven laminates with stacking sequences of $[(0/90^\circ)_5]$. The primary objective is to determine the mechanical properties such as tensile strength, elongation and elastic modulus using standard testing machine, and tested under 0° and 30° orientation. Moreover, the stresses generated among the layers of the glass/polyester lamina was estimated using 2D stress-strain of Hooke law's equations.

Materials and Methods

Materials and Manufacturing

In this study, glass fiber-reinforced polymer (GFRP) composite laminates were manufactured using the VB technique. The reinforcements consisted of five layers of plain-woven glass fiber fabrics, supplied by Spinteks Tekstil İnşaat San. and Tic. A.Ş. The fabric possessed an areal density of 200 g/m². The matrix system used was unsaturated polyester resin, selected for its high mechanical strength and chemical resistance. The physical and mechanical properties of the constituent materials are summarized in Table 1 (Manufacturer's data sheet).

Table 1. Mechanical and physical properties of the reinforcing fibers and matrix.

	Polyester Resin	Glass Fibers	Unit
Density	1.12-1.15	2.6	g/cm ³
Elastic modulus	3.0-3.2	72	GPa
Tensile strength	65	2000	MPa
Tensile elongation	2.6-4.0	2.8	%

The composite plates, with nominal dimensions of 400 times 400 times mm², were designed with three distinct symmetrical stacking sequence of $[(0/90^\circ)_5]$ configuration, resulting in laminates with an average thickness of approximately 1.0 mm. The laminates were fabricated using the VB process. Following the stacking of the 5 plies, the laminates were subjected to a curing cycle at 80°C for a duration of 8 hours. The fiber volume fraction (V_f) of the laminates was 0.55. After resin impregnation, the thickness of each layer was determined to be

approximately 0.185 mm, and the total laminate thickness was approximately 1.1 mm. After curing, the plates were precision-cut into test specimens at orientations of 0°, 30° using water-jet cutting to minimize heat-affected zones and ensure edge quality.

Tensile Testing

Tensile tests were conducted to evaluate the mechanical performance of the manufactured laminates. The experiments were performed at the Middle East Technical University Central Laboratory using a ZwickRoell ProLine Z010 Universal Testing Machine (UTM). Tests were carried out at a constant cross-head speed of 2 mm/min in accordance with international standards, as shown in Figure 1. For each laminate configuration, five specimens were tested, and the results were averaged to ensure statistical reliability.

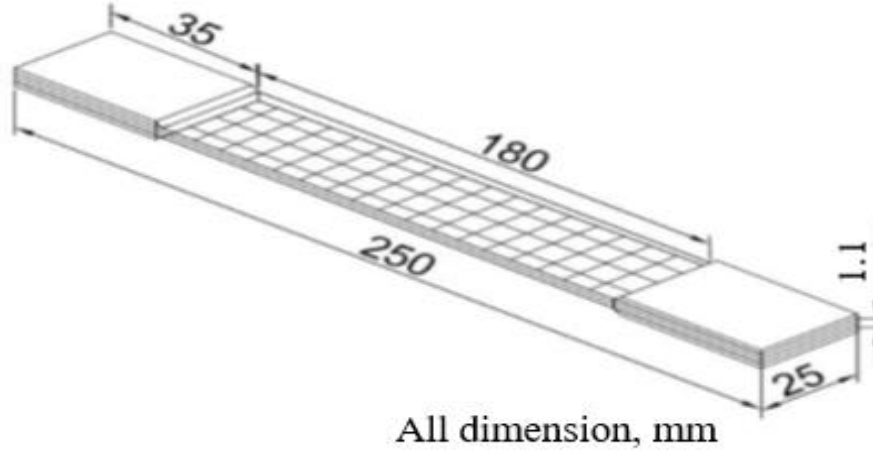


Figure 1. Schematic of composite specimen.

Micromechanical Analysis

The elastic properties of the laminate, including the longitudinal modulus (E_1), transverse modulus (E_2), in-plane shear modulus (G_{12}), Poisson's ratio (ν_{12}), were determined through micromechanical relations in Eqs. (1)–(6) [2].

To predict the tensile modulus of composite, Rule of Mixtures (ROM) was employed. This model assumes perfect interfacial bonding between fibers and matrix. The classical ROM is expressed as:

$$E_1 = E_f * V_f + E_m * V_m \quad (1)$$

where E_1 is the elastic modulus of composite along fiber direction; E_f and E_m are the elastic moduli of the fiber and matrix, respectively; V_f and V_m are their corresponding volume fractions.

The transverse elastic modulus, Poisson's ratio, and in-plane shear modulus were calculated using inverse micromechanical relations:

$$E_2 = \frac{E_f * E_m}{E_m * V_{fe} + E_f * (1 - V_{fe})} \quad (2)$$

$$\nu_{12} = \nu_f * V_{fe} + \nu_m * (1 - V_{fe}) \quad (3)$$

$$G_{12} = \frac{G_f * G_m}{G_m * V_{fe} + G_f * (1 - V_{fe})} \quad (4)$$

Macromechanical Analysis (Classical Laminate Theory)

To determine the mechanical strength of the whole laminate composites the classical laminate theory (CLT) is utilized. By using this CLT, the stresses and strains in local axes can be found by Eq.(1). According to the classical laminated theory (Kaw, 2006), the relation between stress and strain can be expressed as follows:

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \end{bmatrix} \quad (5)$$

The elements of the Q matrix (reduced stiffness coefficients) are dependent on material constants and can be calculated using the following equations: ν_{12}, ν_{21} are poisson's ratios in the 1-2 and 2-1 planes.

$$Q_{11} = \frac{E_1}{1-\nu_{12}\nu_{21}}, \quad Q_{12} = \frac{\nu_{12}E_2}{1-\nu_{12}\nu_{21}}, \quad Q_{22} = \frac{E_2}{1-\nu_{12}\nu_{21}}, \quad Q_{66} = G_{12} \quad (6)$$

where $E_{1,2}$ are the Young's modulus in the direction 1 and 2, G_{12} is the shear modulus in the 1-2 plane,

$Q_{\bar{}}$ also estimated by using the transformation matrix, which is based on the $c=\cos(\theta)$ and $s=\sin(\theta)$ angle.

$$T = \begin{bmatrix} c^2 & s^2 & 2sc \\ s^2 & c^2 & -2sc \\ -sc & sc & c^2 - s^2 \end{bmatrix} \quad (7)$$

Local stress and strains also related to the global stress and strains.

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = [T]^{-1} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix} \quad (8)$$

The above equations are used to determine the stress and strains for a single composite laminate layer. Since the composites are multi-layered structures, equations in this case must be set up in Eq.(9).

$$\begin{bmatrix} N \\ M \end{bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix} \begin{bmatrix} \varepsilon^0 \\ \kappa \end{bmatrix} \quad (9)$$

where N is the vector of resulting forces; M is the vector of resulting moments, ε^0 is the vector of the mid-plane strains; κ is the regarding with the global co-ordinates, as shown in the following equation:

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} = \begin{bmatrix} \varepsilon_{xo} \\ \varepsilon_{yo} \\ \gamma_{xyo} \end{bmatrix} + \begin{bmatrix} K_x \\ K_y \\ K_{xy} \end{bmatrix} \quad (10)$$

where z is an arbitrary distance from the mid-plane. The A, B, D matrix are known as the extensional, coupling and bending stiffness matrices, respectively. Since the composites is symmetrical, $B = 0$ and $D = 0$. The A matrix can be calculated Eq.(11).

$$A_{ij} = \sum_{k=1}^n [\bar{Q}_{ij}]_k (h_k - h_{k-1}) \quad i = 1,2,6; \quad j = 1,2,6, \quad (11)$$

where n is the number of layers; $[\bar{Q}_{ij}]_k$ is the i-th, j-th element of the $[\bar{Q}]$ matrix of the k-th layer; h_k is the distance of the top or bottom of the k-th layer from the mid-plane of the composite laminate.

Under in-plane loading conditions, the governing equation reduces to:

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} \\ A_{21} & A_{22} & A_{26} \\ A_{61} & A_{62} & A_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \end{bmatrix} \quad (12)$$

Under uniaxial tensile loading, only N_x was nonzero other forces N_y, N_z become zero, but axial and transverse strains and shear strain can occur. Thus, the matrix given in Eq.(12) is transformed into a new form to provide the

relation between the N_x and ε_x . Furthermore, the relationship between the internal force per unit width (length) N_x and the strain of mid-plane, ε_{x0} , can be expressed as,

$$N_x = [A]\varepsilon_{x0} \quad (13)$$

Then the axial strain is expressed as,

$$\varepsilon_x = [A]^{-1} N_x$$

Results and Discussion

Experimental Tensile Strength

The tensile tests were carried out to determine the mechanical performance of the GFRP composite laminates at 2 mm/min cross-head speed. The tensile test results of five-ply polyester - glass fiber reinforced composites are presented in Figures 2, 3 for fiber orientations of 0°, 30°, respectively. The fiber volume fraction was about 0.55. To investigate the tensile behavior of the hybrid composite laminates in the direction of the first ply axis (0°), five specimens were prepared and subjected to tensile tests. In all specimens, the 0° plain ply was aligned with the loading direction, thereby maximizing the load-carrying capacity of the fibers under tension.

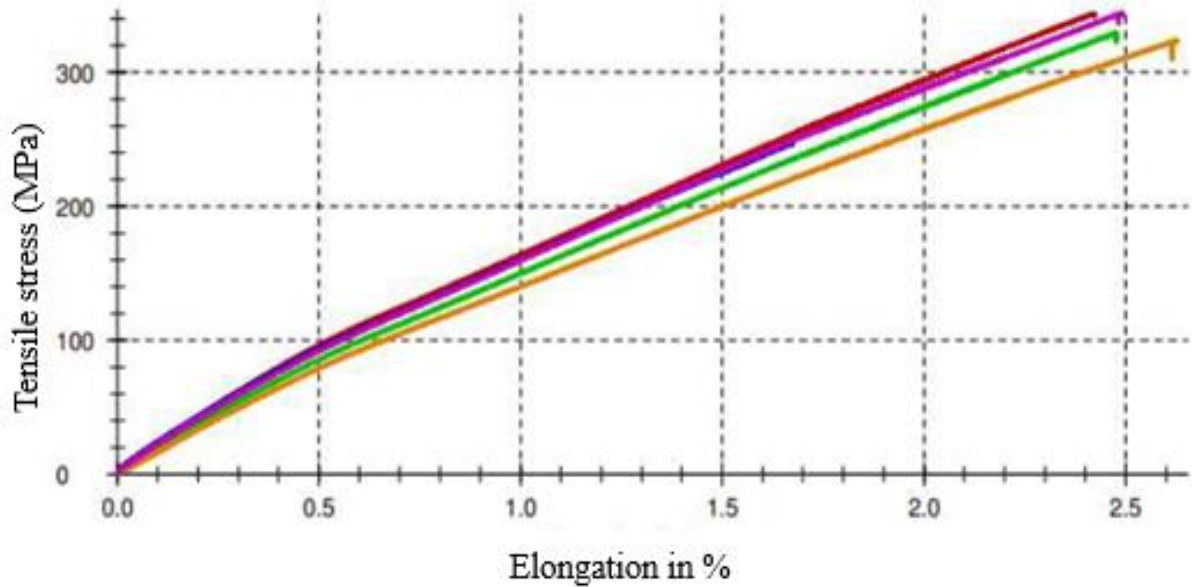


Figure 2. Tensile test results of the GFRP composite laminates at 0° orientation under tensile loading.

The ultimate tensile strengths (σ) ranged from 323.6 MPa to 343.8 MPa, indicating the influence of fiber orientation in the weave structure and minor variations introduced in data. The standard deviation was estimated in terms of four data as about 10.2 MPa. The stress-strain curve displayed a linear elastic response up to failure, with no evidence of yielding or plastic deformation. For only one sample, elongation slightly increased. Failure occurred abruptly following the elastic region at maximum load of approximately 7000 N. The average elongation to failure was measured between 2.5% and 2.7%, with all specimens exhibiting similar elongation at break due to the fiber effect. Additionally, cross-sectional measurements of the test specimens were recorded, and the experimental cross-sectional areas (A_0) were found approximately 22 mm² on average. The elastic modulus was measured from all the specimens. According to the experimental results, the measured elastic moduli varied between approximately 17.136 GPa and 20.979 GPa, and their mean value recorded was at 18.95 GPa. These experimental results are significant in this direction for representing the fiber-dominated load-carrying and stiffness of the pliers. During tensile tests, the elongation values of the test specimens were recorded under loads ranging from 600 N to 7000 N.

Figure 3 illustrates the tensile test results of the GFRP composite laminates at 30° orientation under tensile loading. Five specimens were repeated at this orientation. The ultimate tensile strengths ranged from 103.5 MPa to 121 MPa, indicating the influence of fiber orientation in the weave structure and minor variations occurred in data. The standard deviation was estimated about 6.72. The stress-strain curve was very different, because the

first small area was linear, then it started to plastic deformation region up to about 116 MPa, after this maximum point, decreasing trends were observed. For these samples, elongation increased significantly. Namely, the average elongation to failure was measured over 20%, not all specimens exhibiting similar elongation at break due to the angle-ply fiber and delaminated layers effect. Further, the measured elastic modulus values averaged approximately 10.6 GPa. Failure occurred abruptly following the elastic region at maximum load of approximately 2700 N.

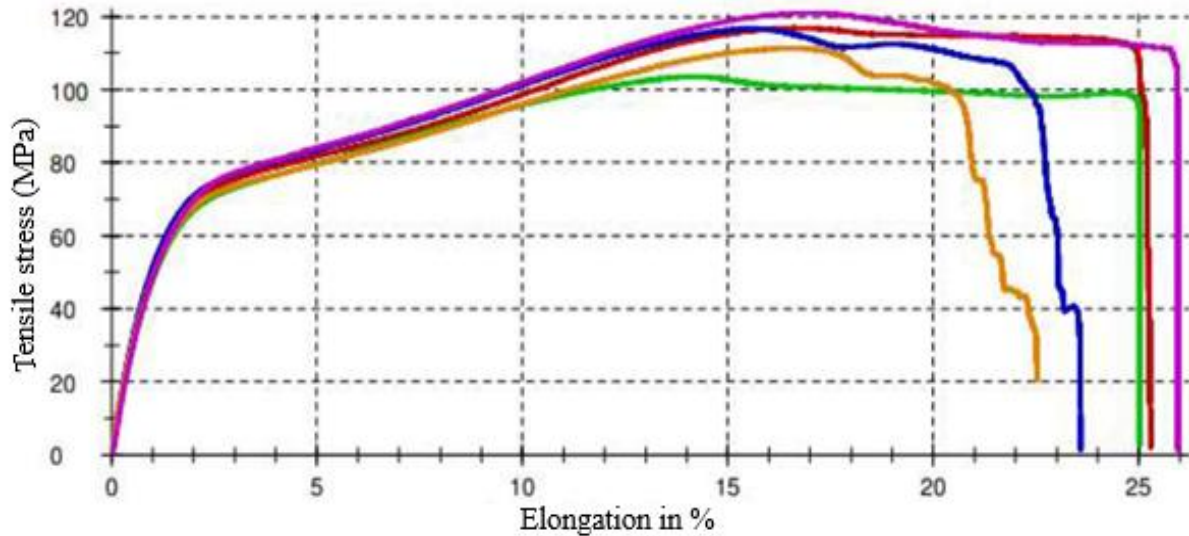


Figure 3. Tensile test results of the GFRP composite laminates at 30° orientation under tensile loading.

Table 2 shows the experimental tensile strength results and standard deviations for the GFRP composites. The results indicate a strong dependence of tensile strength on fiber orientation. The $[0/90^\circ]_5$ laminate composites when tested at 0° exhibited the highest tensile strength (318 MPa), while a considerable reduction was observed for the 30° laminate which is about (114 MPa). These results are quite reasonable, even though glass fibers were used with polyester-based resin. The previous study (Selek&Sahin 2023) on the tensile strength of CFRPs obtained values of approximately 428 MPa and 520 MPa for the 0° and $0/90^\circ$ directions, respectively; for the 45° orientation, the strength was approximately 120 MPa. Comparable studies (Şahin 2024; Cecen&Sarıkant; Özsoy et al. 2015) reported that the tensile performance of the 0° orientation was superior to that of $0/90^\circ$ samples in plain-woven and twill-woven CFRPs, depending on laminate thickness and improved processing conditions. Other researchers (Kumar&Singh 2021; Vinay et al.2022; Abdula &Ibrahim 2025; Kumaresan et al.2015) also reported that the $0/90^\circ$ configuration showed better performance, while off-axis loading resulted in drastic strength reductions for the composites, which is the case for this study.

In the current GFRP samples, the strength enhancement observed in the 0° orientations may result from the longitudinal fibers providing increased resistance. The significant reduction in strength for the off-axis 30° orientation on the conclusion that the resin matrix becomes the primary load-carrier as the fiber orientation deviates from the loading direction, leading to shear-dominated failure modes. Error bars are included exclusively for the experimental data to account for specimen-to-specimen variability. Coefficient variation (CV) also estimated and it ranged from 5.39 to 12.6% are quite reasonable. The measured tensile strength/Young's modulus decreased as the fiber orientation deviated from the loading axis, resulting in the order:

$$(0^\circ) > (30^\circ)$$

Table 2. Experimental tensile strength results for the GFRP composites and their standard deviations.

Lamina. types	Tested composite samples					Measured results		
	1 st sample	2 nd sample	3 rd sample	4 th sample	5 th sample	Mean tensile strength (MPa)	Standard deviations, SD (MPa)	Coefficient variation, CV (%)
0°	343.7	329.2	(247.4)	323.6	344	318	$\pm(40)/10.3$	(12.6)/2.98
30°	116.8	103.5	116.7	111.3	121	113.86	± 6.72	5.90

Elastic Modulus vs. Orientation

The elastic modulus was determined from the slope of the linear elastic region of the stress–strain curves in Figure 2 and 3. Figure 4 shows the experimental elastic modulus comparison of five-ply woven glass/polyester laminates with different fiber orientations 0° and 30° . Error bars are also shown only for the experimental results and represent the corresponding standard deviations (see Table 3). The results clearly demonstrate the strong influence of fiber orientation and fabric architecture on the tensile stiffness of the composites. For 0° orientation, the measured Young's modulus was approximately 18.94 GPa, which is consistent with the stiffness reduction associated with woven fabric architecture and fiber crimp effects while 30° orientation in Young's modulus was measured approximately 10.3 GPa. The composite tested under 30° orientation produced lower rigidity because of dominating the shear + fiber rotation, whereas, the 0° orientation was larger than 30° orientation because of carrying the load along the fiber axis. The standard deviation was estimated for all tested directions. They were approximately 1.47 and 0.28 for 0° and 30° , respectively.

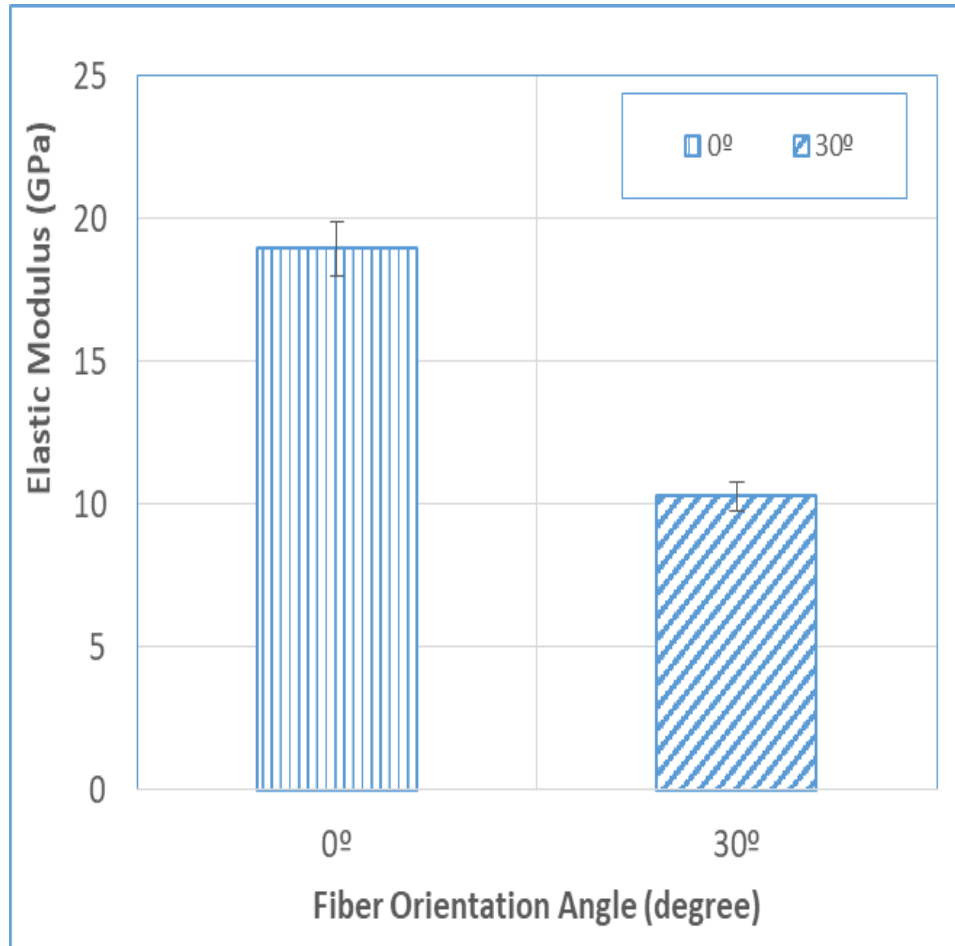


Figure 4. Elastic modulus vs. fiber orientation effects of $[(0/90^\circ)_5]$ laminate composites.

Stresses and Strains on Layers

The behaviour of the laminas is simulated under different loading conditions to understand how to respond to stress and strains. The lamina level is used to describe it as the macroscale. Table 3 depicts the stress and strain induced the each lamina of tested glass/fiber/resin samples under tensile loading conditions. The maximum stresses are developed at the top and bottom lamina (4.085×10^4 Pa), while the minimum stresses (-1.632×10^4 MPa) generated at the second layer and fourth layer of the glass fiber/resin lamina, respectively. The maximum strains generated for 1st ply and 2nd pliers are about 9.9×10^{-7} , 7.78×10^{-8} , respectively. On the other hand, the stress is induced less in the second and fourth layers than the bottom and top lamina of GFRP laminate. The shear stresses and shear angles can be neglected because the obtained values are around 8.121×10^{-14} , -3.5917×10^{-13} and 3.8246×10^{-23} , -1.691×10^{-22} , respectively.

Table 3. Stress and strains induced in the each lamina of the GFRP composites.

Stresses/strains produced among the layers and their levels			
Plies	σ_1	σ_2	τ_{12}
Ply 1 (0°)	4.0851e+04	1.0882e+03	8.1217e-14
Ply 2 (90°)	-1.6323e+04	6.223e+03	-3.5917e-13
Ply 3 (0°)	4.0851e+04	1.0882e+03	8.1217e-14
Ply 4 (90°)	-1.6323e+04	6.223e+03	-3.5917e-13
Ply 5(0°)	4.0851e+04	1.0882e+03	8.1217e-14
Strain (-)			
Plies	ϵ_1	ϵ_2	γ_{12}
Ply 1 (0°)	9.909e-07	-7.785e-08	3.8246e-23
Ply 2 (90°)	-7.785e-08	9.9095e-07	-1.6914e-22
Ply 3 (0°)	9.9095e-07	-7.7853e-08	3.8246e-23
Ply 4 (90°)	-7.7853e-08	9.9095e-07	-3.3827e-22
Ply 5(0°)	9.9095e-07	-7.7853e-08	3.8246e-23

Conclusions

In this study, five-ply plain-woven GFRP laminates were fabricated via the Vacuum bagging method and subjected to experimental investigations. The mechanical response was evaluated across $([0/90^\circ]_5)$ configurations at three different orientations like 0° and 30° , respectively.

The following conclusions are drawn from the investigation:

- The GFRP laminates exhibited a high degree of anisotropy. For the $([0^\circ]_5)$ laminate configuration, the highest tensile strength was obtained at 318 MPa for the 0° direction while the laminate tested at 30° orientation showed the lowest performance was provided at around 114 MPa due to dominant matrix shear and fiber rotation.
- Coefficient deviations remained low, but ranged from 5.39 to 12.64%, indicating a reasonable value.
- The maximum stress is developed at the top and bottom lamina (4.085×10^4 Pa), while the minimum stress is generated at the second and forth layers (-1.63×10^4 Pa) of the glass fiber/polymeric lamina while the shear stresses and shear angles was neglected.
- Overall, this study confirms that twill-woven GFRP laminates offer a versatile balance between stiffness, strength, and energy absorption depending on fiber orientation, and that careful orientation design is essential for tailoring composite performance to specific structural applications.

Further research is recommended to evaluate its applicability to different weave architectures (e.g., satin weave, 3D weave) and manufacturing techniques (e.g., vacuum infusion). It is recommended to employ micromechanical models or advanced numerical simulations (e.g., finite element analysis) by considering the fiber crimp factor that can better represent fiber–matrix interactions.

Scientific Ethic Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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Author(s) Information

Yusuf Sahin

OSTIM Technical University, Department of Mechanical Engineering, , Ostim, Ankara, Türkiye
Contact e-mail: yusuf.sahin@ostimteknik.edu.tr
ORCID iD: <https://orcid.org/0000-0001-9615-6437>

Halil Ridvan Oz

OSTIM Technical University, Department of Mechanical Engineering, Ostim, Ankara, Türkiye
ORCID iD: <https://orcid.org/0000-0002-3032-1388>

Ceren Cetinkaya

OSTIM Technical University, Graduation School of Institute of Science and Technology, Ostim, Ankara, Türkiye
ORCID iD: <https://orcid.org/0009-0001-1245-5657>

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Application of Physics-Informed Neural Networks (PINNs) to Solve a Dynamic Model of Drug Abuse

Chyntia Meininda Anjanni

Gadjah Mada University

Sumardi Sumardi

Gadjah Mada University

Fitri Cahyani

Gadjah Mada University

Abstract: Drug abuse remains a complex and persistent issue in Indonesia, requiring a systematic approach to understand its underlying dynamics. This study applies Physics-Informed Neural Networks (PINNs) as an alternative method for solving the nonlinear differential equations of the $S_n S_e IR$ drug abuse dynamics model. The model divides the population into four compartments: susceptible individuals without education (S_n), susceptible individuals with education (S_e), active users (I), and individuals who have quit or completed rehabilitation (R). The focus of this research is the forward problem, in which the solution of the model is approximated using parameter values obtained from the literature. The PINNs framework combines a data loss term, which measures the discrepancy between predicted solutions and synthetic data, and a physics loss term that enforces consistency with the governing differential equations. The performance of PINNs was first validated by comparing its results with synthetic data generated using the classical fourth-order Runge–Kutta (RK4) method. The model was then further tested using additional synthetic datasets to evaluate generalization. The findings demonstrate that PINNs can successfully approximate the solution of the $S_n S_e IR$ model, yielding continuous and mathematically consistent trajectories that align with the system's dynamics. Moreover, the mesh-free nature of PINNs provides flexibility and computational efficiency, highlighting its potential as a promising tool for analysing complex population-based models.

Keywords: Physics-Informed Neural Networks (PINNs), $S_n S_e IR$ model, Differential equations, Drug abuse dynamics, Forward problem;

Introduction

Drug misuse continues to be a significant public health issue with substantial social and economic consequences. Global reports consistently highlight a rising number of drug users. WHO (2024) estimates that psychoactive substances contribute to hundreds of thousands of deaths annually, while UNODC (2024) reports that more than 296 million people worldwide used illicit drugs in 2021. A similar trend is observed in Indonesia. Data from BNN (2025) indicate that the number of drug users has reached several million, accompanied by high mortality rates and an increasing number of drug-related criminal cases. These findings underscore the need for a systematic understanding of the mechanisms that drive drug-use dynamics within a population.

Mathematical modelling provides a structured framework for analysing such dynamics by dividing the population into compartments and representing transitions between them using differential equations (Boyce, 2017). This approach has been widely adopted to study epidemiological and social processes, including addiction-related behaviours. One model particularly relevant to drug misuse is the $S_n S_e IR$ model introduced by Husain et al.

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(2020), which distinguishes between susceptible individuals without education (S_n) and those who receive preventive education (S_e). This structure enables direct evaluation of how educational interventions influence transitions into drug use. Husain et al. (2020) showed that higher levels of public education can reduce the number of active users and lower the system's basic reproduction number. However, due to its nonlinear structure, the model offers limited analytic tractability, and conventional numerical methods may encounter challenges related to discretisation, accuracy, and stability (Ezadi, 2013; Resmawan, 2023).

Advances in machine learning provide promising alternatives for addressing these limitations. Physics-Informed Neural Networks (PINNs), introduced by Raissi et al. (2017), integrate the governing differential equations directly into the training process of neural networks. Rather than relying solely on data, PINNs ensure that the learned solution adheres to the mathematical laws underlying the system. This approach has demonstrated strong performance in producing accurate, mesh-free solutions across various scientific fields, including biological and epidemiological modelling (Karniadakis, 2021; Farea, 2025).

Despite the increasing use of PINNs in scientific computing, their application to drug abuse dynamics models remains limited. In particular, the $S_n S_e IR$ model incorporating educational interventions has rarely been explored using physics-informed learning approaches. Therefore, investigating whether PINNs can accurately approximate the dynamics of this model becomes an important research question.

Building on these developments, the present study applies PINNs to approximate solutions of the $S_n S_e IR$ drug misuse model using a forward-problem formulation. The model parameters are adopted from Husain et al. (2020). The accuracy of the PINNs approximation is first assessed using synthetic data generated with the classical fourth-order Runge–Kutta (RK4) method (Burden, 2011), followed by additional evaluation using synthetic observational datasets. Overall, this study aims to demonstrate the capability of PINNs as an efficient and flexible tool for analysing complex social dynamics governed by nonlinear differential equations.

Model Formulation

Compartmental models, including the classical Susceptible–Infected–Recovered (SIR) framework introduced by Kermack and McKendrick (1927), have long been used to describe the spread of infectious diseases and other social processes with similar dynamic patterns. While the SIR model provides a fundamental foundation, it does not distinguish different levels of susceptibility nor incorporate preventive interventions. To address these limitations, this study adopts the $S_n S_e IR$ model proposed by Husain et al. (2020), which extends the classical structure by including the influence of educational programs within the susceptible population.

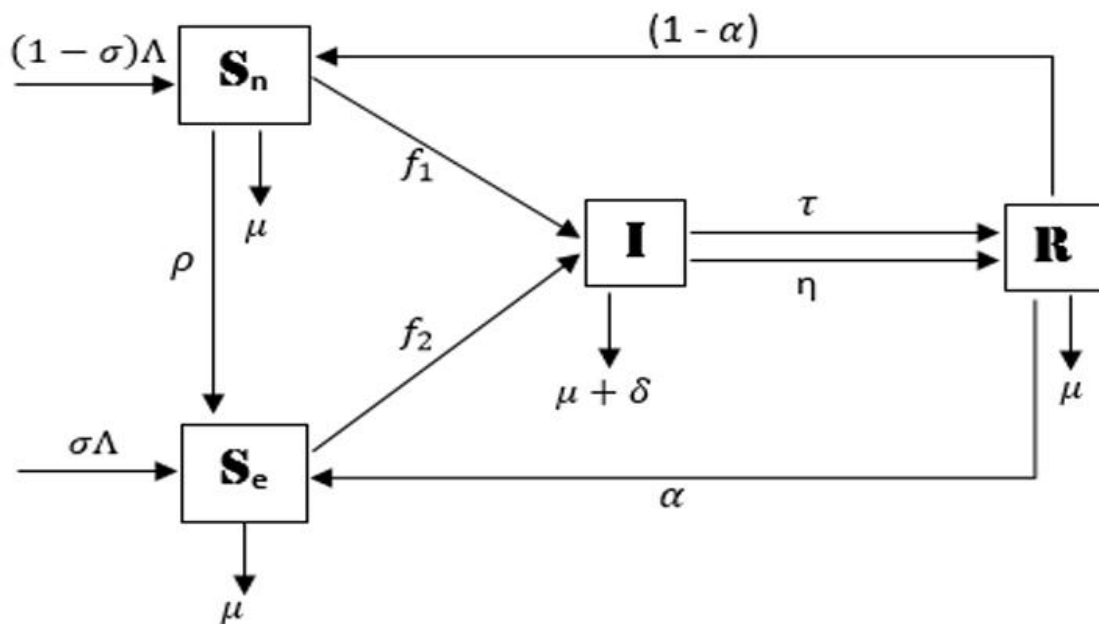


Figure 1. Schematic diagram of the drug-use transmission model
Source: Husain et al. (2020)

To provide a clearer understanding of how individuals transition between compartments, the interaction patterns in the $S_n S_e IR$ model are illustrated through a compartmental diagram. The schematic representation outlines the movement of individuals among susceptible groups (with and without education), active drug users, and those who have recovered or undergone rehabilitation. It also highlights the mechanisms of education, relapse, treatment, and mortality that drive the system's dynamics over time. This diagram serves as a visual guide for interpreting the mathematical relationships that will be formalized in the subsequent differential equations.

The diagram illustrates the flow of individuals among four compartments: susceptible without education (S_n), susceptible with education (S_e), active users (I), and recovered or rehabilitated individuals (R). Recruitment enters the susceptible population with proportions $(1 - \sigma)\Lambda$ for uneducated individuals and $\sigma\Lambda$ for educated individuals. Transitions from S_n to S_e occur at rate ρ , while interactions with active users lead to new users through the incidence terms f_1 and f_2 . Individuals in the I compartment may stop using drugs through voluntary cessation (τ) or rehabilitation (η), moving into the recovery compartment R . A fraction α of those recovered may return to the educated susceptible group, while the remaining $(1 - \alpha)$ re-enter the uneducated susceptible group. All compartments experience natural mortality at rate μ , with an additional mortality rate δ applied to active users. The structure summarizes how educational efforts, relapse, treatment, and behavioral transitions jointly influence the dynamics of drug misuse.

Model Structure

The population is divided into four compartments:

- $S_n(t)$: susceptible individuals without education
- $S_e(t)$: susceptible individuals who have received drug-prevention education
- $I(t)$: active drug users who may influence others
- $R(t)$: individuals who have quit drug use or completed rehabilitation

The total population $N(t)$ is assumed to remain constant, leading to the relationship:

$$S_n(t) = N(t) - (S_e(t) + I(t) + R(t))$$

Table 1. Variables of the $S_n S_e IR$ Model

Variables	Description
$S_n(t)$	Susceptible individuals without education
$S_e(t)$	Susceptible individuals with education
$I(t)$	Active drug users
$R(t)$	Recovered/rehabilitated individuals

Parameters

The model incorporates demographic processes, educational intervention, transmission dynamics, and relapse mechanisms. Parameter definitions are summarised below.

Table 2. Parameters of the $S_n S_e IR$ model

Parameter	Description
Λ	Recruitment rate into the susceptible population
σ	Fraction of newly recruited individuals receiving education
μ	Natural death rate
δ	Additional death rate in the user compartment
ρ	Rate of transition from uneducated to educated susceptibles
β_1	Contact rate between (S_n) and (I)
β_2	Contact rate between (S_e) and (I)
η	Rehabilitation rate of active users
τ	Rate at which users stop using drugs (voluntary cessation)
α	Fraction of recovered individuals returning to (S_e)

Source: Husain et al. (2020)

Following the mass-action incidence formulation described by Hethcote (2000), the contact terms are defined as:

$$f_1 = \beta_1 \frac{S_n I}{N}, f_2 = \beta_2 \frac{S_e I}{N}$$

Educational intervention and relapse dynamics follow the formulation of Li et al. (2018). Recovered individuals may return either to the educated susceptible group S_e with proportion α or to the uneducated group S_n with proportion $1 - \alpha$.

Model Equations

Combining the demographic, educational, transmission, recovery, and relapse mechanisms, the population dynamics are governed by the following nonlinear ordinary differential equations (Husain et al., 2020):

$$\begin{aligned} \frac{dS_n}{dt} &= (1 - \sigma)\Lambda + (1 - \alpha)R - \beta_1 \frac{S_n I}{N} - \rho S_n - \mu S_n, \\ \frac{dS_e}{dt} &= \sigma\Lambda + \rho S_n + \alpha R - \beta_2 \frac{S_e I}{N} - \mu S_e, \\ \frac{dI}{dt} &= \beta_1 \frac{S_n I}{N} + \beta_2 \frac{S_e I}{N} - (\eta + \tau + \mu + \delta)I, \\ \frac{dR}{dt} &= (\eta + \tau)I - \alpha R - \mu R - (1 - \alpha)R. \end{aligned}$$

The resulting system forms a nonlinear ODE model describing the impact of education, interaction rates, cessation, rehabilitation, and relapse on the spread of drug misuse within a population.

Method

This study employs Physics-Informed Neural Networks (PINNs) to approximate the solution of the nonlinear differential equations governing the $S_n S_e I R$ drug misuse model. The methodology consists of several stages: formulation of the compartmental model, generation of synthetic data using a conventional numerical method, construction of the PINNs framework, and validation of the results.

Formulation of the $S_n S_e I R$ Model

The mathematical model used in this study is based on the compartmental formulation developed by Husain et al. (2020). The population is divided into four groups: susceptible individuals without education (S_n), susceptible individuals with education (S_e), active drug users (I), and recovered or rehabilitated individuals (R). The dynamics of each compartment are described by a system of nonlinear ordinary differential equations incorporating recruitment, education, interaction rates, recovery, relapse, and mortality. The complete formulation has been presented in Section 2. This model constitutes the physical law that must be satisfied by the PINNs approximation through its physics-informed loss component.

Synthetic Data Generation Using RK4

Before applying PINNs, synthetic data were generated to serve as reference trajectories for the system. The fourth-order Runge–Kutta (RK4) method was selected because of its stability and accuracy in solving nonlinear differential equations. Using parameter values adopted from Husain et al. (2020), the model was simulated over a fixed time interval with initial conditions chosen to reflect realistic population proportions. The resulting trajectories for $S_n(t)$, $S_e(t)$, $I(t)$, and $R(t)$ were then used both as training supervision, where selected RK4 points contributed to the data-loss term, and as a validation benchmark, where the complete RK4 solution was used to evaluate the accuracy of the PINNs approximation.

Model Parameters

To generate the synthetic data used for training and validating the PINNs model, the $S_n S_e IR$ model system was simulated using a set of parameter values adapted from Husain et al. (2020) and supplemented with reasonable assumptions commonly used in compartmental modelling. These parameters govern the recruitment rate, education effect, transmission intensity, recovery mechanisms, and mortality processes within the population. Since this study focuses exclusively on the forward problem, all parameters remain fixed during the PINNs training phase and are not subject to estimation.

The initial conditions for the simulation were set to

$$S_n(0) = 250, S_e(0) = 200, I(0) = 50, R(0) = 0,$$

representing the initial distribution of individuals across the four compartments. The complete set of parameters used in the simulations is summarised in Table 3.

Table 3. Parameter values used in the simulation of the $S_n S_e IR$ model

Parameter	Description	$R_0 < 1$	$R_0 > 1$	Source
σ	Fraction of new individuals receiving education	0.20	0.40	Assumed
ρ	Education rate from S_n to S_e	0.10	0.10	Assumed
μ	Natural death rate	0.02	0.02	Burattini et al. (1998)
β_1	Transmission rate for S_n	0.12	0.20	Nyabadza dan Musekwa (2010)
β_2	Transmission rate for S_e	0.12	0.20	Nyabadza dan Musekwa (2010)
τ	Voluntary cessation rate	0.01	0.008	Assumed
δ	Additional death rate in I	0.03	0.02	Burattini et al. (1998)
Λ	Recruitment rate	10	14	Assumed
α	Fraction of recovered individuals returning to S_e	0.09	0.09	Assumed
η	Rehabilitation rate	0.15	0.07	Nyabadza dan Musekwa (2010)

Source: Husain et al. (2020)

These parameters determine the qualitative behaviour of the model, including the rate at which individuals transition between susceptibility, education, active use, and recovery. The two parameter sets correspond to scenarios with $R_0 < 1$ and $R_0 > 1$, allowing the system to exhibit different dynamic regimes. In this study, the PINNs framework is evaluated under these fixed parameter configurations to analyse its ability to approximate the forward solution of the model.

PINNs Architecture

The architecture of the Physics-Informed Neural Networks (PINNs) used in this study follows the general formulation for forward problems as presented by Farea et al. (2025). In this framework, the neural network is trained to approximate the solution of a system of nonlinear differential equations while respecting the governing physical laws represented by the mathematical model.

Consider a general ordinary differential equation of the form

$$\frac{dx}{dt} = f(t, x)$$

In the PINNs framework, the unknown solution $x(t)$ is approximated by the output of a neural network defined as

$$\hat{x}(t) = f_N(t; \theta)$$

where θ represents the parameters of the neural network consisting of weights and biases.

Because the governing equation involves derivatives with respect to time, the derivative of the neural network output must also be computed. In PINNs, this derivative is obtained using automatic differentiation as

$$\frac{d\hat{x}(t)}{dt}$$

Based on this formulation, the residual of the differential equation is defined as

$$r(t) = \frac{d\hat{x}(t)}{dt} - f(t, \hat{x}(t))$$

The residual measures how well the neural network prediction satisfies the governing differential equation. If the residual approaches zero, the neural network output satisfies the mathematical structure of the system.

To enforce this condition, the residual is incorporated into the physics-informed loss function defined as

$$\mathcal{L}_f = \frac{1}{N_f} \sum_{i=1}^{N_f} |r(t_i)|^2$$

where N_f denotes the number of collocation points.

In this study, the neural network receives the time variable $t \in [0, T]$ as input and produces a four-dimensional vector representing the approximate solution of the $S_n S_e IR$ system

$$\hat{X}(t) = (\hat{S}_n(t), \hat{S}_e(t), \hat{I}(t), \hat{R}(t))$$

The time derivatives of the network output are computed as

$$\frac{d\hat{X}}{dt}(t) = \left(\frac{d\hat{S}_n}{dt}, \frac{d\hat{S}_e}{dt}, \frac{d\hat{I}}{dt}, \frac{d\hat{R}}{dt} \right)$$

These derivatives are compared with the right-hand side of the dynamical system

$$F(\hat{X}(t)) = (f_{S_n}(t), f_{S_e}(t), f_I(t), f_R(t))$$

The residual of the system at a collocation point t_i is defined as

$$r(t_i) = \frac{d\hat{X}}{dt}(t_i) - F(\hat{X}(t_i))$$

The physics loss is therefore given by

$$\mathcal{L}_f = \frac{1}{N_f} \sum_{i=1}^{N_f} |r(t_i)|^2$$

In addition to the physics loss, the network is trained using synthetic data generated by the classical fourth-order Runge–Kutta (RK4) method. If $X(t_j)$ denotes the reference solution at time t_j , the data loss is defined as

$$\mathcal{L}_d = \frac{1}{N_d} \sum_{j=1}^{N_d} \|\hat{X}(t_j) - X(t_j)\|^2$$

Finally, the total loss minimized during training is expressed as

$$\mathcal{L}_{total} = \lambda_f \mathcal{L}_f + \lambda_d \mathcal{L}_d$$

where λ_f and λ_d are weighting parameters that balance the contribution of the physics loss and the data loss.

The optimisation process is carried out using the Adam optimizer to minimise the total loss function. At each iteration, the parameters of the neural network are updated using gradient-based optimisation computed through automatic differentiation. The training process continues until the loss value converges and the neural network provides a stable approximation of the solution of the $S_n S_e IR$ model.

Collocation Point Selection

Collocation points were placed within the time domain to ensure that the neural network solution adhered to the structure of the differential equations. In this study, the points were selected uniformly across the simulation interval so that the dynamics of the $S_n S_e IR$ system were represented throughout the entire time range. Although the model may contain periods where changes occur more rapidly, especially in the active user compartment $I(t)$, the use of a uniform distribution helps maintain numerical stability during training. When necessary, additional points can be introduced in regions where the solution varies more sharply to improve the accuracy of the residual evaluation.

Training Procedure

The training process was carried out using the Adam optimizer to minimize the total loss function. During each iteration, the parameters of the neural network were updated through gradient-based optimization using automatic differentiation. This process allows the derivatives of the network output with respect to time to be computed accurately and incorporated into the physics-informed loss function. Because this study focuses solely on the forward problem, all model parameters were kept fixed during the training process. The optimization was therefore directed entirely toward learning a continuous approximation of the solution trajectories $S_n(t)$, $S_e(t)$, $I(t)$, and $R(t)$. The training procedure continued until the total loss function reached a stable value and the residuals of the governing differential equations became sufficiently small, indicating that the neural network solution satisfied both the data and the physical constraints of the $S_n S_e IR$ model.

Validation and Evaluation

The performance of the PINNs model was evaluated by comparing its predicted trajectories with the reference solutions obtained from the classical fourth-order Runge–Kutta (RK4) numerical method. The trajectories produced by the neural network were plotted together with the RK4 solutions to examine the level of agreement between the two approaches across the entire simulation interval.

Since this study relies exclusively on synthetic data and does not involve real observational data, the evaluation focuses on how accurately the PINNs approximation reproduces the reference RK4 solution. This comparison allows the reliability of the PINNs method to be assessed in capturing the nonlinear dynamics of the $S_n S_e IR$ model. A close agreement between the predicted trajectories and the RK4 solutions indicates that the PINNs framework is capable of accurately approximating the forward solution of the governing system of differential equations.

Results and Discussion

This section presents the numerical results obtained from applying Physics-Informed Neural Networks (PINNs) to approximate the forward solution of the $S_n S_e IR$ model under two parameter regimes: $R_0 > 1$ and $R_0 < 1$. The accuracy of the method is evaluated by comparing the predicted trajectories with the synthetic benchmark produced using the classical Runge–Kutta fourth-order (RK4) method.

Training Behaviour

The training process was carried out using the Adam optimizer to minimize the total loss function. The total loss decreased smoothly during the training process using the Adam optimizer and reached stable values of

approximately 10^{-4} . This behaviour indicates that the neural network successfully minimized both the data loss and the physics loss while capturing the nonlinear structure of the underlying system of differential equations. The stable convergence also demonstrates that the PINNs framework maintained numerical stability throughout the optimisation process. The small residual values indicate that the neural network solution satisfies the governing differential equations with high accuracy, demonstrating the effectiveness of the physics-informed constraint during the training process.

Results for the $R_0 > 1$ Scenario

When $R_0 > 1$, the system exhibits growth-dominated behaviour in which drug use initially increases before approaching equilibrium. This case presents a more complex transient structure, making it an appropriate test for evaluating the expressive capability of PINNs.

Active Users $I(t)$ and Recovered Individuals $R(t)$

The comparison between PINNs and RK4 for $I(t)$ shows that the network accurately reproduces the initial rise in the number of active users, followed by the gradual decline toward steady state. The early growth reflects the high transmission rates in the $R_0 > 1$ setting, whereas the subsequent decrease corresponds to recovery and mortality processes. The PINNs trajectory closely follows the RK4 solution throughout the simulation, including the peak region where the curve is highly nonlinear. A similar level of agreement is observed for the recovered population $R(t)$. The initial increase in $R(t)$ is captured with precision, illustrating the network's ability to track rapid transitions associated with intensified rehabilitation and cessation. As the system stabilises, the predicted curve remains nearly identical to the RK4 reference, confirming that PINNs can represent long-term behaviour accurately.

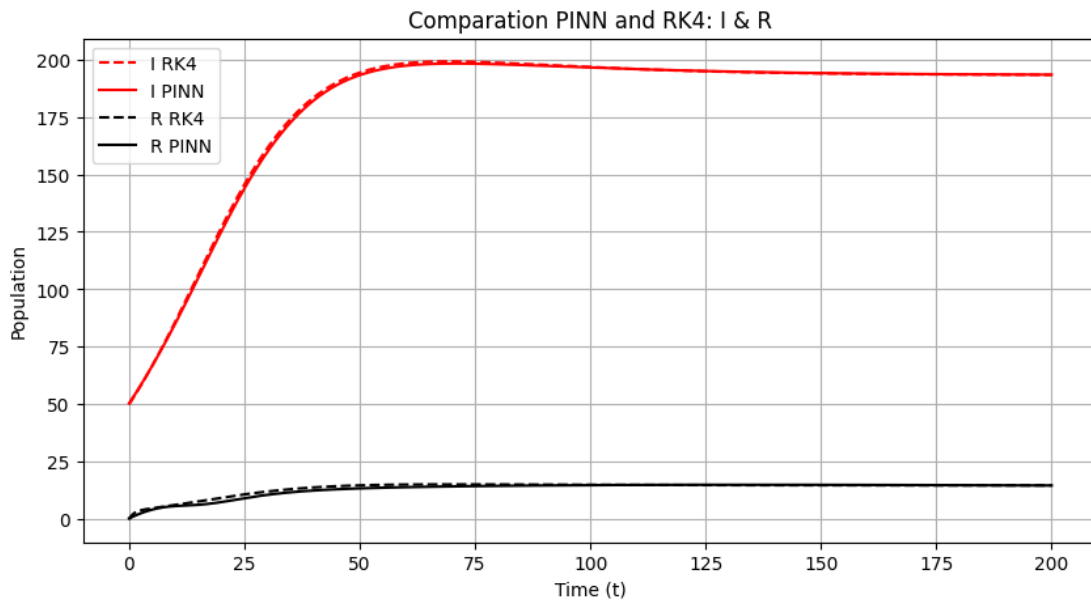


Figure 2. PINNs and RK4 solutions for $I(t)$ and $R(t)$ when $R_0 > 1$

Susceptible Populations $S_n(t)$ and $S_e(t)$

The uneducated susceptible population $S_n(t)$ decreases sharply at the beginning of the simulation due to its interactions with active users. PINNs successfully matches this sharp decline and continues to follow the RK4 curve closely as the system approaches equilibrium. For the educated susceptible group $S_e(t)$, both methods display an initial rapid increase followed by a gradual decrease toward a stable long-term value. This behaviour reflects the strong influence of education-related transitions in the $R_0 > 1$ regime. The close overlap between the two methods shows that PINNs can capture the full trajectory, including its transient rise and asymptotic decline.

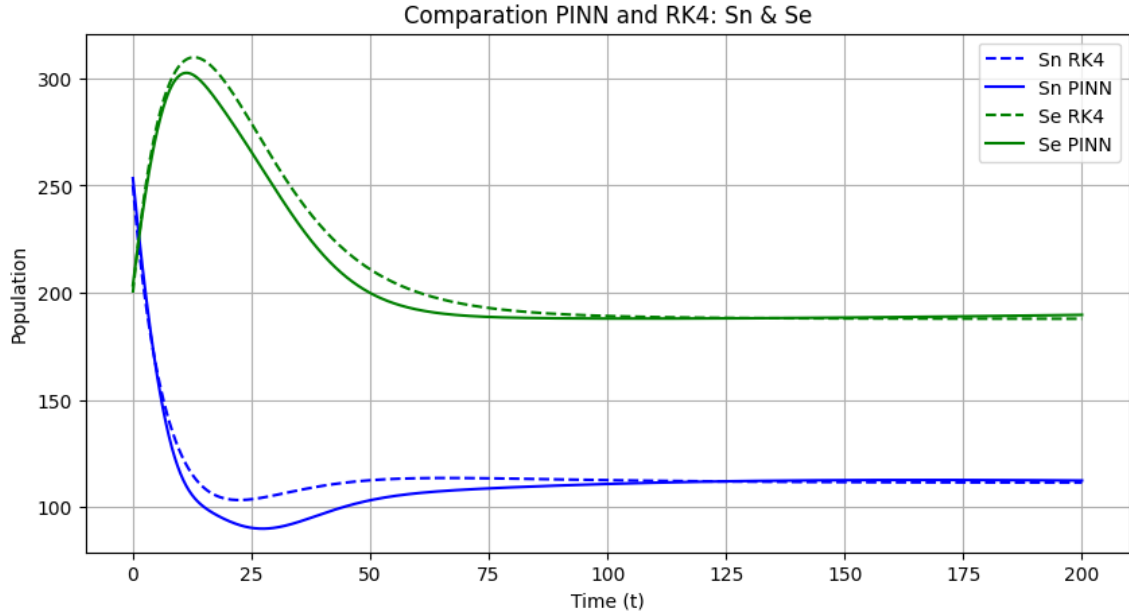


Figure 3. PINNs and RK4 solutions for $S_n(t)$ and $S_e(t)$ when $R_0 > 1$

Interpretation for the $R_0 > 1$ Case

Overall, the $R_0 > 1$ results reveal a system that experiences an early escalation in drug use, accompanied by substantial changes in the susceptible and recovered populations. PINNs is able to replicate these dynamics with a high degree of accuracy. The nearly perfect alignment of the predicted curves with the RK4 solutions suggests that the method is capable of learning both the rapid transient phase and the eventual stabilisation of the system.

Results for the $R_0 < 1$ Scenario

The $R_0 < 1$ regime represents a decay-dominated system in which drug use diminishes over time. This case is useful for assessing the network's ability to capture rapid decreases and long-term convergence toward a drug-free equilibrium.

Active Users $I(t)$ and Recovered Individuals $R(t)$

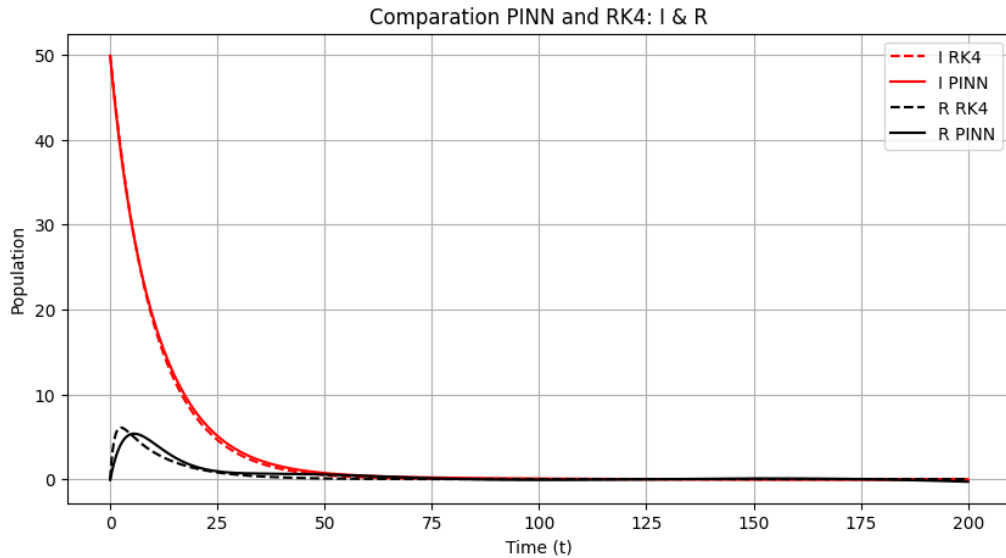


Figure 4. PINNs and RK4 solutions for $I(t)$ and $R(t)$ when $R_0 < 1$

In this scenario, $I(t)$ declines very rapidly from the initial condition. The PINNs approximation mirrors this steep exponential decline almost exactly, demonstrating the network's ability to reproduce fast transitions without numerical oscillation. As $I(t)$ approaches zero, the two solutions remain indistinguishable. For the recovered population $R(t)$, both methods show a small increase at early times followed by a gradual descent toward equilibrium. The PINNs curve matches the RK4 reference throughout the entire time domain, capturing both the mild curvature of the early phase and the smooth long-term behaviour.

Susceptible Populations $S_n(t)$ and $S_e(t)$

The behaviour of the susceptible populations reflects the decaying influence of drug users. The uneducated susceptible group $S_n(t)$ decreases quickly at first and then rises slowly as the number of active users approaches zero. PINNs reproduces this transition without deviation from the RK4 curve. The educated susceptible population $S_e(t)$ shows a modest initial increase followed by gradual convergence to a stable value, and the PINNs approximation remains consistent with the RK4 solution across the entire interval.

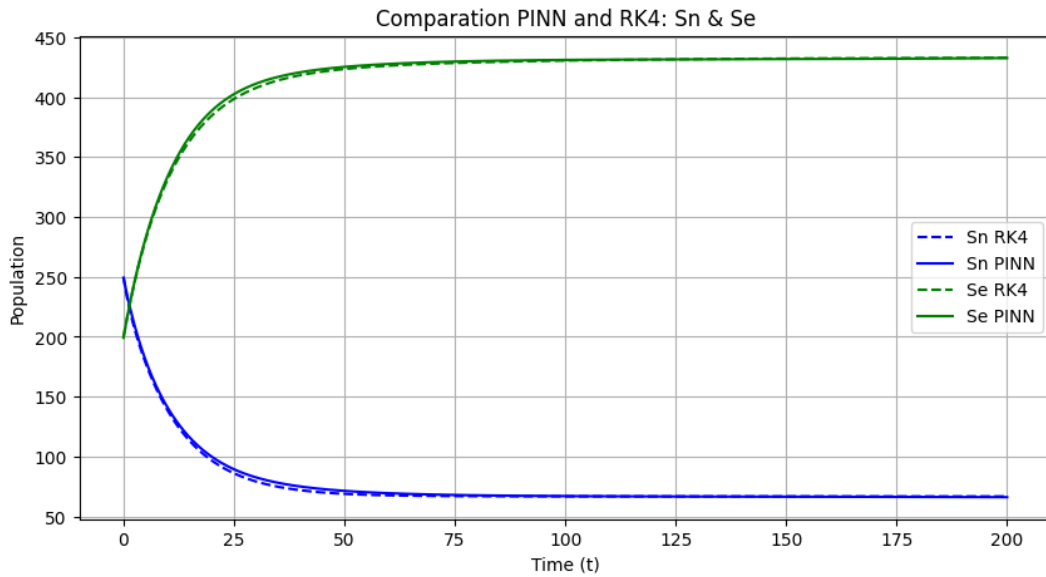


Figure 5. PINNs and RK4 solutions for $S_n(t)$ and $S_e(t)$ when $R_0 < 1$

Interpretation for the $R_0 < 1$ Case

The results for $R_0 < 1$ illustrate a system in which drug use declines rapidly and eventually disappears. All compartments move smoothly toward equilibrium as the influence of active users diminishes. The PINNs solutions are virtually identical to the RK4 benchmarks, indicating that the method is able to approximate decay-dominated dynamics with high precision.

The results demonstrate that the PINNs model successfully reproduces the RK4 numerical solutions for all compartments under both dynamic regimes. In the $R_0 > 1$ scenario, the network accurately captures the initial growth of active drug users followed by stabilization toward equilibrium. In contrast, when $R_0 < 1$, the system exhibits a rapid decay of the active user population toward a drug-free equilibrium. The close agreement between the PINNs predictions and the RK4 solutions confirms that the proposed approach can effectively approximate the nonlinear dynamics of the model.

Conclusion

This study applied Physics-Informed Neural Networks (PINNs) to approximate the forward solution of the $S_n S_e I R$ drug-misuse model and evaluated their performance using synthetic data generated through the classical fourth-order Runge–Kutta method. The results demonstrate that PINNs are capable of reconstructing the system's nonlinear dynamics with high accuracy across both parameter regimes considered, namely $R_0 > 1$ and $R_0 < 1$.

The predicted trajectories closely match the RK4 benchmark for all compartments, including those exhibiting rapid transitions such as the active-user population. The network produced smooth and dynamically consistent solutions while maintaining numerical stability throughout the optimisation process. These findings confirm that PINNs can faithfully integrate the governing differential equations into their learning process, enabling them to capture both transient behaviour and long-term equilibrium in a mesh-free manner. Given their ability to approximate complex dynamical systems with limited data, PINNs offer a promising alternative to traditional numerical solvers for modelling population-based social or epidemiological processes.

Future work may extend this framework to the inverse problem setting, allowing the estimation of key model parameters from real observational data, or explore broader applications that incorporate uncertainty quantification and more complex intervention structures.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM Journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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Author(s) Information

Chyntia Meininda Anjanni

Gadjah Mada University
Yogyakarta, Indonesia

*Contact e-mail: chyntiameinindaanjanni@mail.ugm.ac.id
ORCID iD: <https://orcid.org/0009-0002-5108-6759>

Sumardi Sumardi

Gadjah Mada University
Yogyakarta, Indonesia

ORCID iD: <https://orcid.org/0000-0002-7925-9351>

Fitri Cahyani

Gadjah Mada University
Yogyakarta, Indonesia

ORCID iD: <https://orcid.org/0009-0006-8290-6763>

* Corresponding author(s) email

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Physics-Informed Neural Networks (PINNs) for Parameter Estimation in the SIRS-D Epidemiological Model

Fitri Cahyani

Gadjah Mada University

Abdurakhman Abdurakhman

Gadjah Mada University

Chyntia Meininda Anjanni

Gadjah Mada University

Abstract: Infectious diseases exhibit complex and rapidly evolving transmission dynamics, requiring modeling approaches that can accurately capture these mechanisms. The SIRS-D compartmental model provides a suitable framework, as it incorporates temporary immunity and disease-induced mortality within the epidemic process. Accurate parameter estimation is essential for quantifying the transmission rate, recovery rate, waning immunity rate, and mortality rate, which collectively govern the system behavior. Among existing estimation methods, Physics-Informed Neural Networks (PINNs) offer significant advantages by integrating observational data with the underlying structure of differential equations, thereby preserving physical consistency while maintaining robustness under imperfect data conditions. In this study, PINNs are employed to estimate the parameters of the SIRS-D model using synthetic data generated through the fourth-order Runge–Kutta (RK4) method to ensure stable and consistent numerical solutions. To better represent real-world measurement conditions, 5% noise is added to the synthetic data, introducing realistic variability into the training process. The results demonstrate that PINNs successfully reconstruct the trajectories of $S(t)$, $I(t)$, $R(t)$, and $D(t)$ with low prediction errors. The model achieves MAE values of 0.0065 (S), 0.0067 (I), 0.0208 (R), and 0.0043 (D), with corresponding RMSE values of 0.0090, 0.0074, 0.0253, and 0.0058. Moreover, the estimated parameters closely match the true values, yielding $\beta = 0.5031$, $\gamma = 0.0996$, $\delta = 0.0095$, and $\omega = 0.0149$, demonstrating strong parameter identification capability. These findings confirm that PINNs constitute a reliable and accurate framework for analyzing infectious disease dynamics and offer promising potential for extension to more complex epidemiological models and real-world datasets.

Keywords: Physics-informed neural network, SIRS-D model, Estimation parameter, Runge-kutta

Introduction

Infectious diseases remain a recurring global health challenge due to their rapid transmission and widespread impact. Many infectious diseases also exhibit the possibility of reinfection, such as seasonal influenza, pertussis, and other respiratory viral infections that do not provide long-term immunity. This phenomenon of reinfection makes epidemiological models that account for immunity loss an important component in understanding the dynamics of disease transmission (Hethcote, 2000).

The SIRS-D model itself is an extension of the SIRS model, which initially consisted of three compartments: susceptible, infected, and recovered. In the SIRS model, individuals who recover may become susceptible again after their immunity wanes, making it suitable for representing diseases that allow reinfection, including infectious diseases such as COVID-19. The SIRS-D model then adds a death compartment, allowing both reinfection dynamics and mortality risks to be represented more realistically for diseases with a certain fatality level.

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Parameter estimation in the SIRS-D model, such as the transmission rate, recovery rate, immunity loss rate, and mortality rate, plays a crucial role in understanding the characteristics of disease spread. With advancements in modern computational methods, Physics-Informed Neural Networks (PINNs) have increasingly been used because they integrate data with the mathematical structure of differential equation models, enabling the learning process to remain aligned with the true system dynamics (Raissi et al., 2019). PINNs have also been shown to be effective in various epidemiological and dynamical system studies because they can produce stable estimates even when data are limited (Cuomo et al., 2022; Millevoi et al., 2024; and Farea et al., 2025).

Several studies demonstrate that PINNs are an effective approach for analyzing dynamical systems governed by differential equations. This method has been applied in biomedicine to reconstruct cardiac electrical activation, and in epidemiology by Berkahn & Ehrhardt (2022) and Han et al. (2024) to analyze COVID-19 transmission and estimate epidemiological parameters directly from data. In addition, Ouyoussef et al. (2024) showed that PINNs can estimate transmission parameters in a two-group epidemic model with high accuracy, while Farea et al. (2025) demonstrated that PINNs can solve forward and inverse problems in the SIR model with excellent reconstruction performance. These findings highlight the significant potential of PINNs in epidemiological model analysis, especially for parameter estimation when data availability is limited.

In this study, PINNs are used to estimate the parameters of the SIRS-D model. The training data were obtained through numerical simulation using the fourth-order Runge–Kutta method to ensure that the synthetic data generated were consistent and controlled. Through this approach, the study aims to evaluate the capability of PINNs in learning the dynamics of the SIRS-D model, assessing the quality of parameter estimation, and exploring the potential application of this method in compartmental epidemiological models for infectious diseases characterized by reinfection and notable mortality rates.

Physics-Informed Neural Networks (PINNs)

PINNs are a machine learning approach that integrates physical laws into the training process of artificial neural networks. Unlike conventional models that rely solely on observational data, PINNs incorporate differential equation systems, both ODEs and PDEs, as part of the loss function. Consequently, the resulting solution not only fits empirical data but also remains consistent with the underlying system dynamics.

In general, the architecture of PINNs consists of an input layer, several hidden layers with nonlinear activation functions, and an output layer that produces the predicted state variables $\hat{x}(t)$. Its main uniqueness lies in the combined loss function, which includes the error relative to the data and the residual of the differential equations. During training, the network seeks to minimize both components simultaneously, allowing the model to follow data patterns while still satisfying physical laws. The following is the architecture of PINNs as presented in Figure 1.

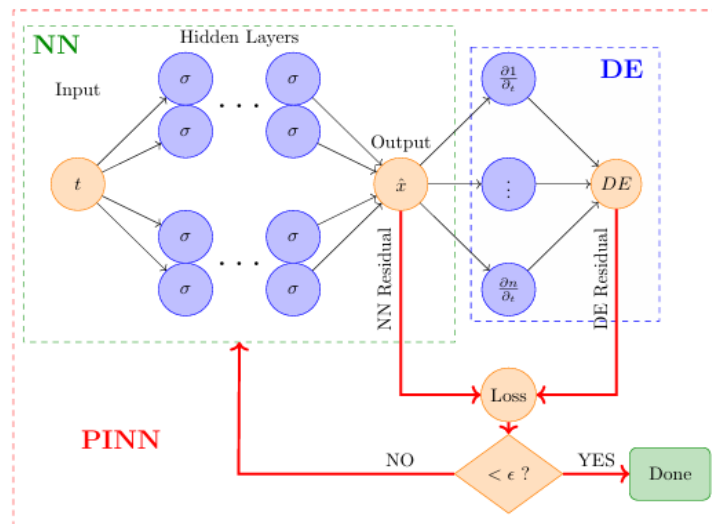


Figure 1. PINNs' architecture (Farea et al., 2025)

During training, PINNs aim to minimize the combined loss function:

$$\mathcal{L}_{total} = \lambda_1 \mathcal{L}_{data} + \lambda_2 \mathcal{L}_{physics}$$

with $\mathcal{L}_{data}$ representing the error between the neural network predictions and the observational data, while $\mathcal{L}_{physics}$ measures the extent to which the network predictions satisfy the system of differential equations. The weights λ_1 and λ_2 are used as balancing factors between accuracy with respect to the data and adherence to physical laws.

The data loss component is computed using the Mean Squared Error (MSE), whereas the physics loss evaluates the residuals of the differential system through automatic differentiation. Automatic differentiation technology, such as that provided in PyTorch, enables PINNs to compute time derivatives accurately without requiring additional numerical schemes. This approach allows PINNs to handle nonlinear problems without linearization or local time-stepping.

$$\mathcal{L}_{data} = \frac{1}{N} \sum_{i=1}^N (\hat{x}(t_i) - x(t_i))^2 \quad (1)$$

with $\hat{x}(t_i)$ represents the neural network's predicted value at time t_i , while x_i is the actual observed value at the same time.

Meanwhile, the physics loss component ensures that the solution remains consistent with the modeled dynamics:

$$\mathcal{L}_{physics} = \frac{1}{N} \sum_{i=1}^N \left(\frac{d\hat{x}(t_i)}{dt} - f(\hat{x}, t_i) \right)^2 \quad (2)$$

$f(\hat{x}, t_i)$ is a functional form of the system of differential equations that describes the relationships among the variables in the model and $\frac{d\hat{x}(t_i)}{dt}$ in the equation above is computed automatically using PyTorch's automatic differentiation framework.

In epidemiological modeling such as SIRS-D, PINNs can be used to estimate unknown parameters, such as the transmission rate, recovery rate, disease-induced mortality, and loss of immunity. The training process employs optimization algorithms such as Adam to update the network weights and model parameters until the loss function reaches a certain tolerance value. In this way, PINNs provide solutions that are consistent with the data while also adhering to the underlying differential system dynamics.

SIRS-D Model

The SIRS-D (Susceptible–Infected–Recovered–Susceptible–Deceased) model is an extension of compartmental epidemiological models used to analyze the dynamics of infectious disease transmission. This model originates from the basic SIR framework and is further expanded by adding a death compartment as well as a mechanism that allows recovered individuals to return to the susceptible class, thereby representing the possibility of reinfection. With this structure, the SIRS-D model provides a more realistic depiction of transmission, recovery, and disease-induced mortality.

The model divides the population into four main compartments based on their epidemiological status at time t : susceptible $S(t)$, infected $I(t)$, recovered $R(t)$, and deceased $D(t)$ (Zinihi et al., 2025). The total population N is assumed to remain constant over time and is defined as the sum of individuals across all compartments. In this study, the compartmental variables are expressed in proportions, such that each compartment takes values between 0 and 1, making the total population $N = 1$.

$$S(t) + I(t) + R(t) + D(t) = 1 \quad (3)$$

The dynamics of transitions between compartments are determined by four parameters. The transmission rate β describes the rate at which the disease spreads from infected individuals to susceptible individuals. The recovery rate γ represents the proportion of infected individuals who recover per unit time. The parameter δ characterizes the disease-induced mortality rate, while the parameter ω describes the rate of immunity loss that allows recovered individuals to become susceptible again. The presence of the parameter ω enables the SIRS-D model to capture reinfection phenomena commonly observed in certain infectious diseases. Assuming that transmission occurs through direct contact between susceptible and infected individuals, the dynamics of each compartment are expressed through the following system of differential equations:

$$\begin{aligned}
 \frac{dS(t)}{dt} &= -\beta S(t)I(t) + \omega R(t) \\
 \frac{dI(t)}{dt} &= \beta S(t)I(t) - \gamma I(t) - \delta I(t) \\
 \frac{dR(t)}{dt} &= \gamma I(t) - \omega R(t) \\
 \frac{dD(t)}{dt} &= \delta I(t)
 \end{aligned}
 \tag{4}$$

Several assumptions are used to simplify the simulation process and parameter estimation using PINNs. First, the population is assumed to be closed, meaning that the total population remains constant throughout the simulation period; in other words, no births or natural deaths occur aside from disease-induced mortality. Second, transmission is assumed to occur through direct contact between susceptible and infected individuals, so the transmission rate depends on interactions between these two compartments. Third, individuals who have recovered may experience a loss of immunity and return to the susceptible class, allowing reinfection to occur. Fourth, the parameters β , γ , δ , and ω are assumed to be constant over time, although their values are estimated during the PINNs training process. Fifth, the initial proportions of each compartment are assumed to be known at the start of the simulation. These assumptions are used to keep the model simple while still capturing the fundamental dynamics of disease transmission with reinfection.

Method

Data Source

This study utilizes synthetic data to evaluate the capability of Physics-Informed Neural Networks (PINNs) in estimating parameters of the SIRS-D model. The synthetic data were generated numerically based on the system of differential equations of the SIRS-D model using predetermined parameter values. The data generation process was carried out by solving the differential equation system numerically using the fourth-order Runge–Kutta (RK4) method with 5% added noise. This method was chosen due to its good accuracy and stability in modeling epidemic dynamics. Through the RK4 scheme, approximate solutions at each time step can be computed systematically, resulting in population dynamics curves for each compartment, namely $S(t)$, $I(t)$, $R(t)$, and $D(t)$.

By using fully controlled data, the performance of PINNs can be evaluated more clearly, as the true parameter values and actual underlying dynamics are known in advance. Furthermore, the use of synthetic data enables researchers to ensure that the model operates consistently before being applied to real-world data, which are typically more complex and contain observational uncertainties. The following is a plot of the data generated using the fourth-order Runge–Kutta method.

Methodology

The method used in this study is a numerical experiment based on synthetic data. The research steps are as follows:

1. Determining the basic parameters of the SIRS-D model ($\beta, \gamma, \delta, \omega$) which serve as references for generating synthetic data.
2. Generating synthetic data by constructing the SIRS-D system of differential equations and solving it using the fourth-order Runge–Kutta method to obtain the dynamics of $S(t)$, $I(t)$, $R(t)$, and $D(t)$.
3. Splitting the synthetic data into training and testing datasets with an 80:20 ratio (96 for training and 24 for testing).
4. Defining the architecture of the PINNs model with time t as input and the estimated outputs $\hat{S}(t)$, $\hat{I}(t)$, $\hat{R}(t)$, and $\hat{D}(t)$.
5. Training the PINNs model on the training dataset by minimizing a loss function that combines prediction error on synthetic data and the residuals of the differential equations, resulting in parameter estimates consistent with the system dynamics.
6. Evaluating the PINNs model by calculating MAE and RMSE using the testing data.
7. Analyzing the parameter estimation results to assess the ability of PINNs to identify epidemiological parameters based on synthetic data.

Results and Discussion

The data used in this study consist of synthetic data generated from the SIRS-D model. The generation of synthetic data is carried out to provide a fully controlled testing environment, allowing the evaluation of the capability of Physics-Informed Neural Networks (PINNs) in estimating parameters to be performed more clearly and systematically.

This synthetic data is obtained by numerically solving the system of differential equations of the SIRS-D model using the fourth-order Runge–Kutta (RK4) method with 5% added noise. RK4 was chosen because it offers a good balance between accuracy and stability, especially when used to model the dynamics of infectious diseases. Through the RK4 scheme, approximate solutions are computed incrementally at each time step, resulting in the population evolution curves for the susceptible $S(t)$, infected $I(t)$, recovered $R(t)$, and deceased $D(t)$ compartments. In this study, the data generation process was performed using predetermined baseline parameters, namely $\beta=0.5$, $\gamma=0.1$, $\gamma=0.01$, $\omega=0.015$, $S(0)=0.999$, $I(0)=0.001$, $R(0)=0$, dan $D(0)=0$.

The simulation time span is set from $t = 0$ to $t = 60$, with a total of 120 data points, ensuring a uniform time step throughout the simulation. With this parameter configuration and numerical scheme, a series of data reflecting epidemic dynamics consistent with the SIRS-D model is obtained. These data are then used as input to train and evaluate the PINNs model. Since the true parameter values are known, the model performance can be assessed directly through the ability of PINNs to reconstruct both the parameters and the solution curves that approximate the true underlying dynamics.

Figure 1. presents the plot of the synthetic data generated using the RK4 method with 5% added noise, illustrating the population changes in each compartment over the simulation period.

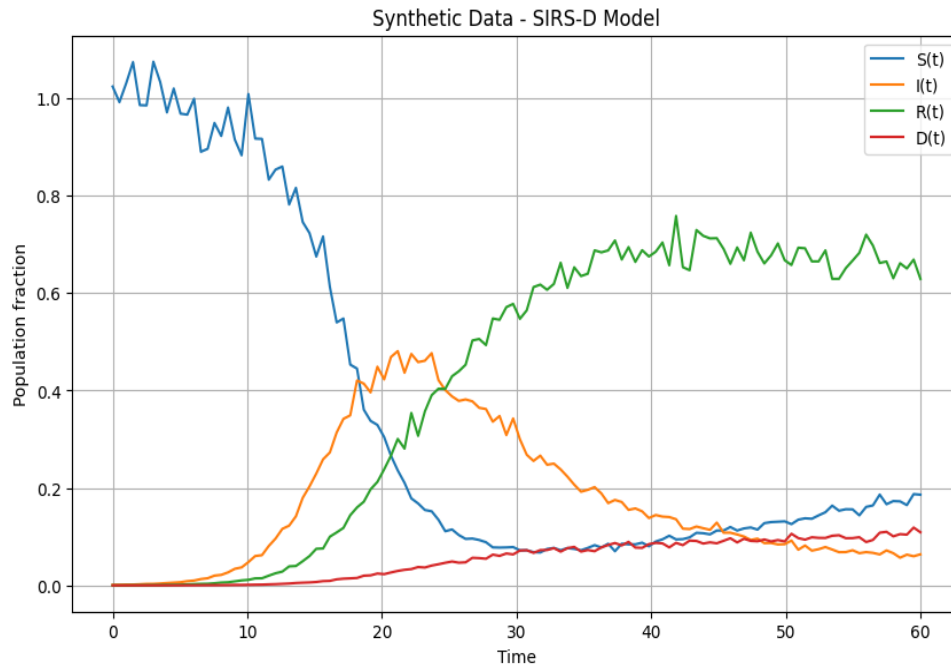


Figure 1. Synthetic data

Physics-Informed Neural Networks (PINNs) Simulation for Parameter Estimation

At this stage, the Physics-Informed Neural Networks (PINNs) model is constructed and trained to estimate the parameters and reconstruct the solution dynamics of the SIRS-D model. The entire training process is carried out using PyTorch, with the network architecture and training parameters configured to ensure stable learning from both the synthetic data and the physical information derived from the differential equations. The network architecture used is a feedforward neural network with a single input representing the time variable t , and four outputs corresponding to the functions $S(t)$, $I(t)$, $R(t)$, and $D(t)$. The network consists of three hidden layers with 30, 40, and 50 neurons, respectively. Each layer is connected through sigmoid activation functions, chosen

for their smoothness and suitability in supporting automatic differentiation, which is central to the PINNs approach.

The training process is carried out using the Adam optimizer, as it is capable of accelerating convergence and performs well on complex objective functions. The learning rate is set to 1×10^{-4} , while the numerical tolerance parameter (epsilon) in the optimizer is assigned a small value of 2.9×10^{-4} to maintain computational stability during weight updates. The loss function used is a combination of data loss and physics loss, with respective weights of 0.3 and 0.7 (Farea et al., 2025). This weighting emphasizes that the network should not only fit the observational data but also satisfy the physical structure defined by the differential equations of the SIRS-D model. Through this approach, the resulting solution is expected to be mathematically consistent rather than merely following the pattern of the data points.

Training is performed for a maximum of 50,000 epochs, or terminated earlier if the model reaches convergence. Under this configuration, the total computational time required to complete the training process is approximately 2 minutes and 27 seconds, which is relatively efficient for a PINNs model with four outputs. The following presents the convergence results of the PINNs loss.

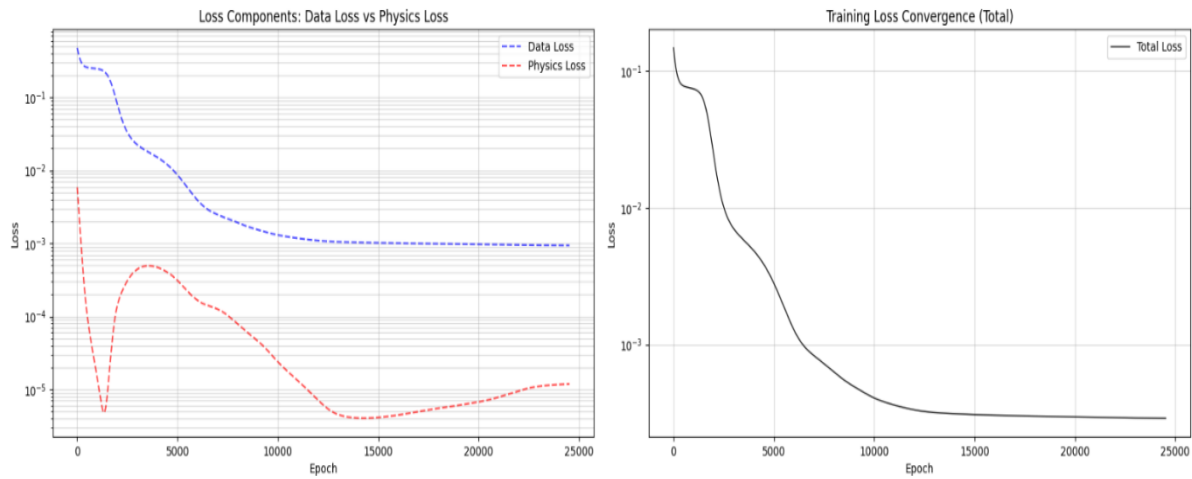


Figure 2. Convergence analysis of PINNs' loss

The left panel shows the evolution of the individual loss components during the PINNs training process, namely the data loss and the physics loss. The data loss (blue dashed curve) decreases steadily throughout training, starting from 10^{-1} and gradually approaching the order of 10^{-3} . This consistent decline indicates that the network progressively improves its fit to the synthetic observations of $S(t)$, $I(t)$, $R(t)$, and $D(t)$. In contrast, the physics loss (red dashed curve) exhibits a more dynamic pattern. At the beginning of training, its value drops sharply, followed by a temporary increase around the mid-training phase. This behavior reflects the adjustment process in PINNs, where the network simultaneously attempts to minimize the discrepancy with data and satisfy the governing differential equations. After this transitional phase, the physics loss decreases again and stabilizes at a very small magnitude, indicating that the physical constraints of the SIRS-D model are increasingly well satisfied.

The right panel presents the total training loss, which combines both data and physics components. The curve demonstrates a clear convergence pattern. In the early epochs, the total loss decreases rapidly, showing that the network quickly captures the dominant structure of the problem. As training progresses, the rate of decrease becomes more gradual, indicating parameter refinement. Toward the end of training, the total loss reaches a stable plateau at a very small value and no longer exhibits significant oscillations. This stable convergence suggests that the selected network architecture, activation function, and Adam optimizer effectively guide the training process.

Overall, both figures confirm that the PINNs model achieves a balanced optimization between data fitting and physical consistency. The stable behavior of the loss components indicates that the network has successfully learned the epidemic dynamics represented by the SIRS-D system and is ready for further evaluation through predictive analysis and visualization.

The four panels depict the evolution of the estimated parameters β , γ , δ , and ω obtained using PINNs, compared with their respective true values (red dashed lines). Each curve illustrates how the network gradually refines the parameter values throughout the training process. For β , the estimate initially starts below the true value of 0.5

and shows moderate fluctuations during the early epochs. After this initial adjustment phase, the curve increases steadily and approaches the reference value. In the later stages of training, the estimate stabilizes very close to 0.5, indicating successful convergence. A similar convergence behavior can be observed for γ . The estimated value first exhibits noticeable oscillations, including an early overshoot above the true value of 0.1, followed by a temporary decline. As training progresses, the curve gradually corrects itself and converges smoothly toward 0.1, with minimal variation near the final epochs.

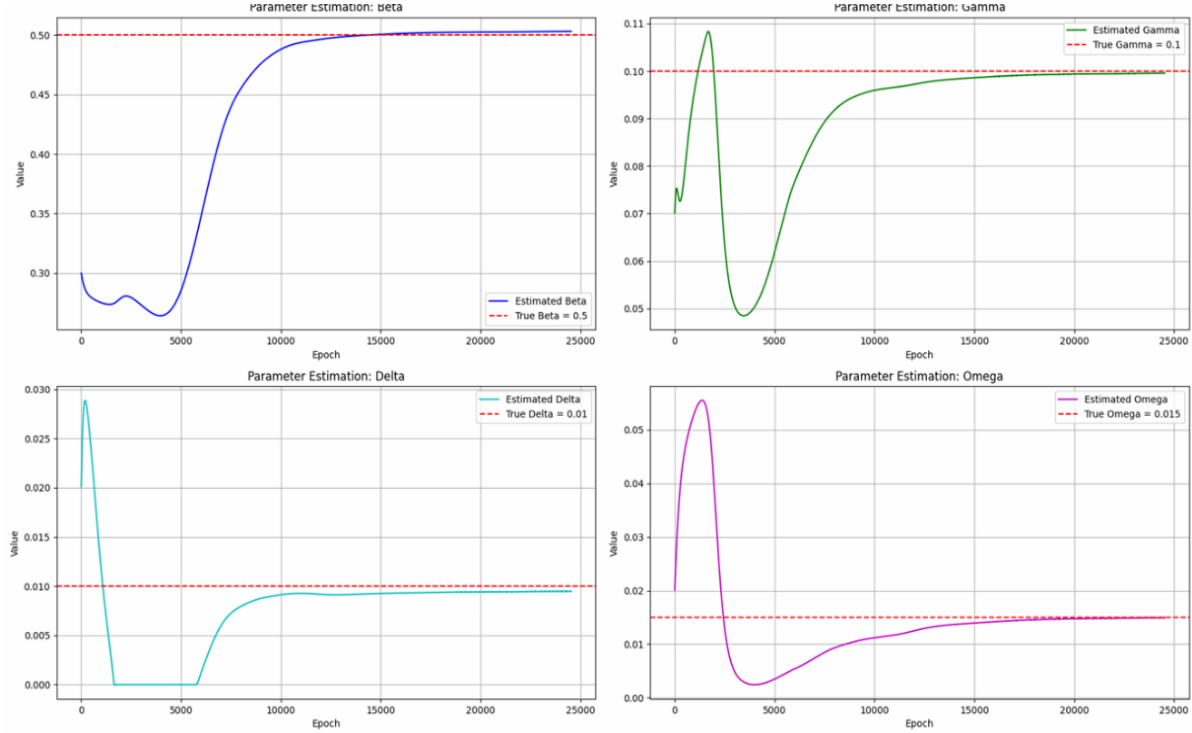


Figure 3. Convergence analysis of parameter estimation

The estimation of δ shows a sharp drop at the beginning of training, reaching values close to zero. This early instability is followed by a gradual increase, and the curve eventually stabilizes near its true value of 0.01. The delayed stabilization reflects the relatively small magnitude of this parameter and its weaker influence on the system dynamics during the early learning phase. Among all parameters, ω exhibits the most pronounced early fluctuations, including a significant spike followed by a sharp decrease. However, after several thousand epochs, the estimate begins to increase steadily and ultimately converges toward the true value of 0.015. The stabilization in the final stage indicates that the network successfully captures the waning immunity effect represented by this parameter. Overall, despite the distinct transient behaviors observed in the early training phase, all parameter estimates progressively approach their true values and remain stable toward the end of training. This consistent convergence demonstrates that the PINNs framework is capable of accurately and reliably identifying the parameters of the SIRS-D model.

To evaluate the ability of the PINNs model to make predictions on the testing data, two main metrics are used: Mean Absolute Error (MAE) and Root Mean Square Error (RMSE). These metrics are commonly used to measure how closely the model's predictions match the actual values. MAE measures the average absolute difference between predictions and actual data, and is defined as:

$$MAE = \frac{1}{N} \sum_{i=1}^N |y_i - \hat{y}_i| \quad (5)$$

Meanwhile, RMSE provides an error measure that assigns a larger penalty to large deviations, and is expressed as:

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (y_i - \hat{y}_i)^2} \quad (6)$$

The following are the results of the MAE and RMSE calculations:

Table 1. Testing dataset evaluation

Variables	MAE	RMSE
S	0.0065	0.0090
I	0.0067	0.0074
R	0.0208	0.0253
D	0.0043	0.0058

Table 1 summarizes the testing performance of the PINNs model for each compartment: S , I , R , and D . The MAE and RMSE values for all variables are relatively small, lying approximately in the order of 10^{-3} to 10^{-2} . This indicates that the predicted solutions are close to the reference data across all compartments. The S compartment yields an MAE of 0.0065 and an RMSE of 0.0090, showing good agreement between the predicted and true susceptible population. For the I compartment, the MAE and RMSE are 0.0067 and 0.0074, respectively, which also reflect accurate reconstruction of the infected dynamics. The R compartment presents slightly higher errors (MAE = 0.0208 and RMSE = 0.0253) compared to the other variables. Nevertheless, these values remain relatively small and indicate that the recovery dynamics are still well captured by the model. Meanwhile, the D compartment exhibits the lowest error values (MAE = 0.0043 and RMSE = 0.0058), suggesting that the model effectively approximates the death dynamics despite the smaller magnitude typically associated with this compartment. Overall, the results in Table 1 demonstrate that the PINNs framework provides accurate predictions for all components of the SIRS-D system. The consistently low error values confirm that the model successfully learns the patterns contained in the synthetic dataset while preserving the underlying physical structure of the differential equations.

Following the evaluation of predictive performance, the next step is to examine the model's capability in parameter identification. This aspect is essential to verify whether the network truly captures the governing dynamics of the SIRS-D system rather than merely fitting the data. The comparison between the estimated parameters and their true values is presented in Table 2.

Table 2. True parameters vs estimation parameters

Parameters	True values	Estimation values
β	0.5	0.5031
γ	0.1	0.0996
δ	0.01	0.0095
ω	0.015	0.0149

Table 2 presents a comparison between the true parameter values of the SIRS-D model and the corresponding estimates obtained using the PINNs framework. The results demonstrate that all parameters, namely β , γ , δ , and ω , are identified with a high degree of accuracy. The estimated values are remarkably close to the true parameters, with only marginal deviations observed in the fourth decimal place. Specifically, the estimated transmission rate β (0.5031) closely approximates its true value of 0.5. Similarly, the recovery rate γ is estimated as 0.0996, which is highly consistent with the reference value of 0.1. The mortality rate δ and the waning immunity rate ω are also reconstructed with minimal discrepancies, yielding estimated values of 0.0095 and 0.0149 compared to their true values of 0.01 and 0.015, respectively.

The close agreement between the true and estimated parameters confirms that the PINNs approach is capable not only of accurately reconstructing the state variables $S(t)$, $I(t)$, $R(t)$, and $D(t)$, but also of reliably identifying the intrinsic parameters governing the interactions within the SIRS-D system. This consistency indicates that the network successfully integrates observational data with the embedded physical constraints derived from the differential equations. These findings provide strong evidence that PINNs constitute an effective framework for parameter identification in epidemiological models, particularly when the training process is supported by well-defined physical structures and high-quality data. Following the parameter estimation analysis and the evaluation of predictive accuracy using MAE and RMSE metrics, the next step is to visually compare the PINNs predictions with the synthetic data over both the training and testing intervals. The subsequent figure illustrates the model's capability in reconstructing the overall epidemic dynamics represented by $S(t)$, $I(t)$, $R(t)$, and $D(t)$.

The graph below illustrates the comparison between the synthetic data and the PINNs predictions for $S(t)$, $I(t)$, $R(t)$, and $D(t)$ over both the training and testing intervals. The vertical dashed line indicates the boundary between the training and testing regions. Within the training domain, the predicted trajectories closely follow the observed data points for all compartments. The susceptible population $S(t)$ exhibits a gradual decline, which is accurately captured by the model. The infected compartment $I(t)$ shows a clear epidemic peak followed by a steady decrease, and this characteristic pattern is well reconstructed by the PINNs solution. Similarly, the recovered population

$R(t)$ demonstrates a monotonic increase before approaching saturation, while the deceased compartment $D(t)$ grows progressively over time. These dynamic behaviors are consistently reproduced by the predicted curves, indicating that the network successfully learns the intrinsic structure of the epidemic process.

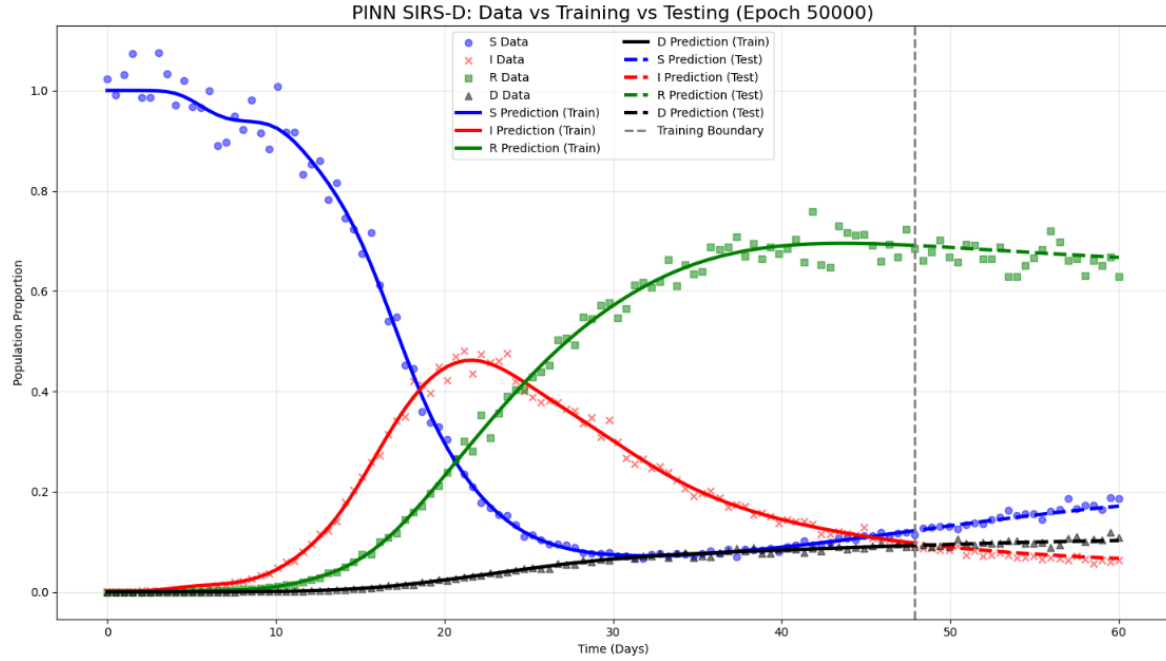


Figure 4. Comparison of real data and PINN predictions for the SIRS-D model

Importantly, the agreement between predictions and data remains strong in the testing region beyond the training boundary. The smooth continuation of all trajectories without significant deviation suggests that the model does not merely interpolate within the training data but is also capable of generalizing the learned dynamics to unseen time intervals. Overall, the close alignment between synthetic data and predicted solutions across all compartments confirms the robustness and reliability of the PINNs framework in representing the SIRS-D epidemic dynamics. The results demonstrate that the model effectively integrates observational information with the governing differential equations to produce accurate and physically consistent predictions.

Conclusion

This study demonstrates that Physics-Informed Neural Networks (PINNs) are capable of accurately reconstructing the dynamics of the SIRS-D model and estimating epidemiological parameters using synthetic data generated through the fourth-order Runge–Kutta (RK4) method with 5% added noise. The use of RK4 enables the production of smooth, stable, and system-consistent data, providing a strong foundation for evaluating the capability of PINNs.

The training process yields stable loss convergence, as reflected by the decreasing data loss and physics loss to very small values. Evaluation using MAE and RMSE metrics shows that the PINNs predictions closely match the testing data across all compartments, $S(t)$, $I(t)$, $R(t)$, and $D(t)$, indicating highly accurate reconstruction of the solution trajectories. The parameter identification results also demonstrate strong performance, with the estimated values of β , γ , δ , and ω being nearly identical to the true parameters used in generating the synthetic data. This high level of agreement confirms that PINNs not only fit the data well but also effectively capture the physical structure of the differential equations underlying the SIRS-D model.

Overall, this study shows that PINNs are an effective and reliable approach for learning the dynamics of differential equation–based disease models, both in predicting solution trajectories and estimating fundamental model parameters. These findings open opportunities for further applications to other epidemiological models, including those involving real-world data that are more complex and contain substantial uncertainty.

Recommendations

This study uses synthetic data to ensure that PINNs are capable of reconstructing the SIRS-D dynamics and estimating parameters under idealized conditions. For future work, it is recommended to apply the model to real-world data (e.g., daily case reports from health agencies or publicly available epidemiological datasets) so that the performance of PINNs can be evaluated under more realistic and uncertainty-prone conditions. When transitioning to real data, several considerations should be taken into account: perform data cleaning and preprocessing (handling missing values, applying smoothing if necessary, and normalization), adjust the loss formulation to address noise (e.g., by adding regularization or using robust loss functions), and consider time-varying parameters to capture actual changes in epidemiological dynamics.

Scientific Ethics Declaration

* The scientific ethical and legal responsibility of this article published in EPSTEM Journal belongs to the authors.

Conflict of Interest

* The authors have no conflicts of interest in any area.

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Author(s) Information

Fitri Cahyani

Universitas Gadjah Mada

Yogyakarta, Indonesia

ORCID iD: <https://orcid.org/0009-0006-8290-6763>

*Contact e-mail: fitricahyani192@gmail.com

Abdurakhman Abdurakhman

Universitas Gadjah Mada

Yogyakarta, Indonesia

ORCID iD: <https://orcid.org/0000-0003-0758-5323>

Chyntia Meininda Anjanni

Universitas Gadjah Mada

Yogyakarta, Indonesia

ORCID iD: <https://orcid.org/0009-0002-5108-6759>

*Corresponding author(s) email

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Adnan M. Al-Smadi

Zarqa University
Yarmouk University

Hazem Jihad Badarneh

Zarqa University

Ghadeer Zidan Sulieman

Al al-Bayt University

Abstract: The increasing complexity of vehicle electronics and conventional fuel systems have elevated the risks of gas leaks and fires. In addition, high-density batteries in Electric Vehicles (EVs) raises the risk of fire. Vehicle fires represent a significant safety hazard, causing hundreds of deaths and billions in property damage annually. One of the main dangers related with firefighting operations is the harmful ambience resulted from combusting materials. The four main hazards related to these cases are smoke, the oxygen insufficient atmosphere, high temperatures, and toxic ambience. Hence, fire is a real danger and fire safety is a critical issue in vehicle's industry. This paper proposes a real-time intelligent vehicle gas and fire detection and suppression system. The system uses Arduino Microcontroller based-system that integrates multi-sensor data fusion capable of detecting gas, smoke, over-temperature and combustion. The system uses alarm signaling devices, solenoid valve, fire-extinguishing equipment, and feeders for the fire-extinguishing substance. This comprehensive vehicle safety system provides multi-layered protection against gas leaks, fires, and overheating and automatic response without driver intervention. Hence, it is capable of detecting and suppressing fire. In addition, the system is interfaced to GSM network to enable wireless communication through SMS.

Keywords: Vehicle safety, Fire detection, Gas leak detection, Arduino microcontroller

Introduction

Fires represent a serious threat to humans, property, and the environment. It is a disaster that threatens people's lives and properties including vehicles (Saraev, 2025). Timely detection and effective extinguishing are essential to reduce harmful consequences. Vehicles' fires in transportation occur regularly. In recent years a significant number of severe fires in vehicle depots have occurred, mostly resulting in the loss of a larger number of vehicles (Hofmann et al., 2025). Vehicle fires are among the most severe risks faced by transportation industries. From buses carrying passengers to small private cars, fire outbreaks can result in catastrophic losses of lives and properties. There are several reasons for vehicle fires such as fuel leakage, engine overheating, and electrical short circuits. Another reason is where a vehicle caught in an accident. If the fire is not suppressed in time, the driver and his company and the vehicle would be in big threat. Sometimes, it is difficult to suppress a fire in a vehicle using hand fire extinguisher because of the fierce fire. In addition, fires in electrical vehicles pose significant safety concerns in modern vehicle systems (Mishra et al., 2025).

Recently, Lithium-Ion Batteries (LIB) are increasingly used in devices people interact with daily. They are found in several instruments such as smartphones, laptops and vehicles. However, they possess significant

safety risks, especially regarding fires. The probability of LIB to over-heat or even to catch on fire increases when incorrectly charged or used (Scarfogliero et al., 2018).

As people use electric vehicles (EVs), LIB technology has a major role in the vehicle because of its characteristics such as power. However, the age and the expected lifetime of the LIB are still under study and investigation. LIB aging is affected by several factors such as temperature and current rate (Scarfogliero et al., 2018). Hence, these batteries are responsible for an increasing number of fire incidents. For example, LIB operates best between 15°C and 45°C. low temperatures (<15°C) have a risk of lithium dendrite forming which can cause short circuits. High Temperatures (>40°C) can lead to releasing flammable gases and increasing explosion risks (Tai et al., 2024).

Researchers are constantly putting efforts into developing better and more reliable automatic vehicle fire suppression methods and technologies to provide the market with safer vehicles. This paper proposes the design and rationale for an intelligent vehicle gas and fire detection and suppression system. The system uses Arduino Microcontroller based-system that integrates multi-sensor data fusion capable of detecting gas, smoke, over-temperature and combustion. The system uses alarm signaling devices, solenoid valve, relay, fire-extinguishing equipment, and feeders for the fire-extinguishing substance. Hence, the system is capable of detecting and suppressing fire. In addition, the system is interfaced to Global System for Mobile Communications (GSM) network to enable wireless communication through Short Message Service (SMS).

Proposed System

Vehicles' fires in transportation occur regularly. Timely detection and effective suppressing are essential to reduce harmful consequences. In this paper, we propose an intelligent vehicle gas detection and suppression system using Arduino Microcontroller. The system integrates various sensors to detect gas, smoke, over-temperature, flames, combustion and extinguish fire in the vehicle. The Arduino Microcontroller is the brain of the system. The system includes in addition to the Arduino, MQ2 gas/smoke sensor, REES52 IR flame sensor, LM35 temperature sensor, buzzer, relay, solenoid valve, water pump, SG90 servo motor, Light Emitting Diode (LED), Liquid Crystal Display (LCD), and GSM. Fire safety is ensured through flame and gas sensors, triggering immediate alerts. The suppression system utilizes relay, solenoid valve and a spray nozzle system. The block diagram of the proposed intelligent safety system is shown in Figure 1.

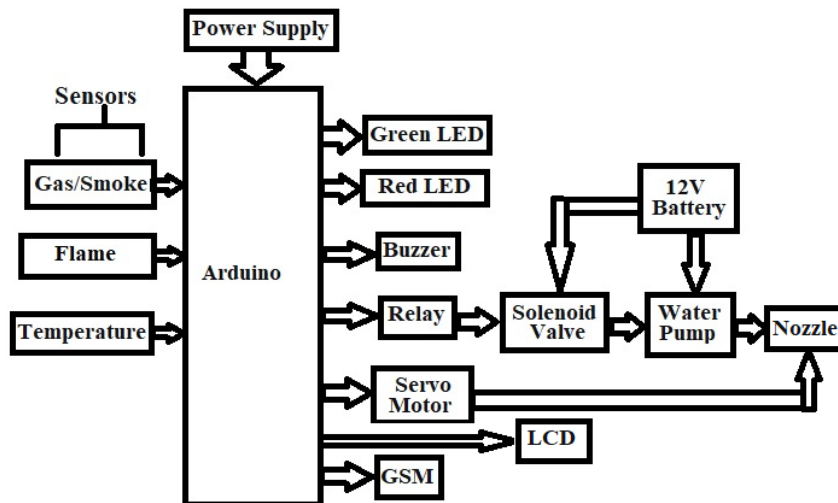


Figure 1. Block diagram of the proposed intelligent vehicle safety system

The major components of the proposed intelligent fire and gas detection system in the block diagram are described here.

Arduino Microcontroller

“Arduino microcontroller is an open-source board used to design and build electronic circuits. It is a low-cost device and is easy-to-use hardware and software” (Al-Smadi et al., 2020). Arduino board has digital and analog

inputs' and outputs' pins. Arduino board can read inputs from sensors and instruments, turn them into output commands that can activate other parts such as LED. Figure 2 displays an Arduino microcontroller board.

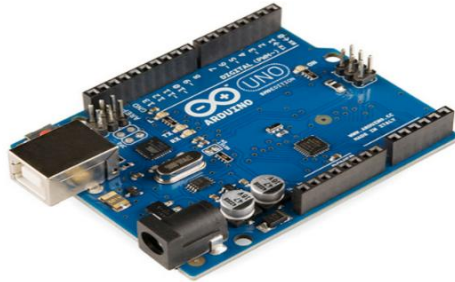


Figure 2. Arduino microcontroller (Al-Smadi et al., 2020)

MQ2 Gas/Smoke Sensor

MQ2 gas/smoke sensor used for detecting the concentration (leakage) of smoke and various gases in the atmosphere such as liquefied petroleum gas (LPG), methane, carbon monoxide and propane (Babu et al., 2024, Wang et al. 2023). It contains a small heater with an electrochemical part to measure different kind of gases. MQ2 sensor has a sensing material whose resistance changes with the type of gas in the atmosphere. That is, when one type of gas touches the sensor after heating, the sensor's resistances change. Hence, the voltage across the sensor changes which will be read by the Arduino Microcontroller. This sensor is used to detect the leakage of harmful gases. It has an analog output signal which can be read by the Arduino analog input. The MQ2 gas/smoke detector is shown in Figure 3.



Figure. 3. MQ2 gas sensor pinout

REES52 IR Flame Sensor

The REES52 infrared (IR) flame sensor is a vital component for fire detection and safety systems (Al-Smadi et al., 2024). This specialized module employs an infrared sensor to detect the presence of flames. The IR Flame Sensor for Arduino is a highly sensitive sensor that can detect the presence of IR radiation emitted by flame. It converts this detection into a digital voltage signal. It is convenient to use with the Arduino microcontroller and can be integrated into a wide diversity of applications such as fire detection systems and home security. The REES52 IR flame sensor is shown in Figure 4.



Figure 4. REES52 IR flame sensor

LM35 Temperature Sensor

This sensor is realized for its precision in temperature measurement when the output voltage is linearly proportional to the Celsius, °C, temperature (Shuvu & Chowdhury, 2024). It is designed with no need for further calibration, so it can be used where simple and accurate temperature tracking is recorded. The output scale factor of the LM35 temperature sensor is 10 mV/°C. Hence, to calculate the temperature, the voltage (mv) in output pin is divided by 10. The range of temperature that the sensor can measure is from -55°C to 150°C. The pin diagram for the LM35 sensor is shown in Figure 5.

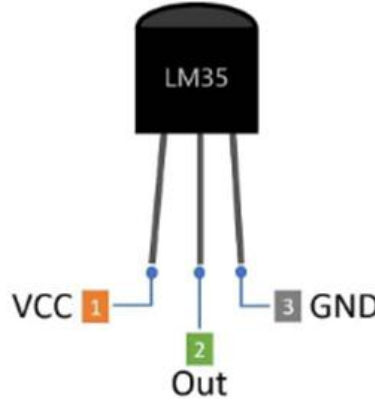


Figure 5. LM35 sensor pin diagram

Actuation Unit

The SG90 is a servo motor used to rotate an object to a particular angle or position. The angle of the servo motor is controlled by the Arduino. It has three wires: power, ground and signal. The servo is low power controlled by Pulse Width Modulation (PWM) signal, with a duty cycle of 600µs to 2400µs (measured), and a total period of 20ms (50Hz) (Al-Smadi et al., 2026). The Arduino generates the PWM signals to make the servo motor work. Figure 6 shows the SG90 Servo Motor pinout. Servo motor can make rotation about 180° (90° in each direction).

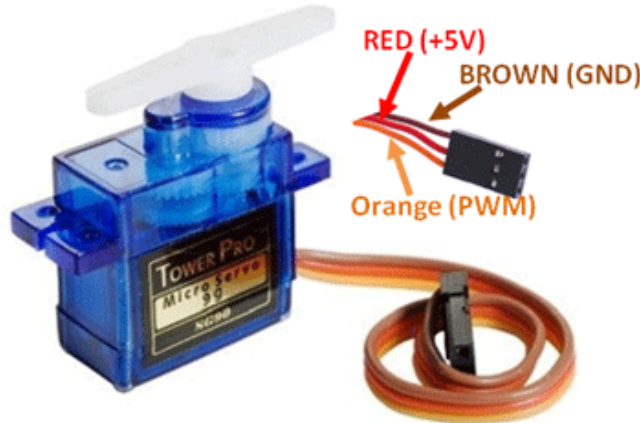


Figure 6. SG90 servo motor pinout

Solenoid Valve

The solenoid converts electrical signals into mechanical motion. A water solenoid valve is an electromechanical device that controls and regulates the flow of water by opening (or closing) in response to an electric current (Fan, 2025). A solenoid valve consists of three main components: a solenoid (an electric coil), a plunger (or armature), and a valve body. As an electric current goes through the solenoid, it generates a magnetic field that moves the plunger within the coil, allowing or stopping the flow of water. Water solenoid valves play a significant role in handling water flow in different applications. A water solenoid valve is shown in Figure 7.



Figure 7. Water solenoid valve

Relay

A relay is an electrically operated switch. As an electrical current goes through the coil, it generates a magnetic field that activates the contacts (armature which connects or disconnects the circuit). Hence, a relay is a switch that is used to turn on and off electrical circuits in response to a low-current control signal (Al-Smadi et al., 2019). Figure 8 shows a typical relay.

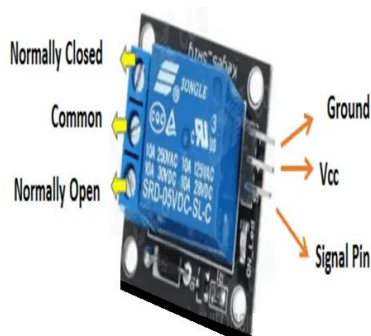


Figure 8. Typical relay

System Implementation

The block diagram in Figure 1 shows the components of the proposed intelligent vehicle gas and fire detection and suppression system. The central intelligence of the system is the Arduino microcontroller. The Arduino has three main functions: processes inputs, compares with thresholds and makes decisions, and triggers outputs.

All other parts of the system are connected to the Arduino microcontroller. The core components of the system include an Arduino microcontroller board, gas/smoke sensor, flame sensor, temperature sensor, LCD, actuation unit, solenoid valve, relay, water pump, and GMS. The sensors enable monitoring environmental conditions, and the detection of potential gas/smoke and fire hazards. The system utilizes solenoid valves and a spray nozzle system to automate fire suppression. Hence, the Arduino acts as the microcontroller, reading sensor inputs, processing logic, and sending commands to the actuators. It's the central hub that orchestrates the entire detection and suppression process.

Gas/smoke sensor (MQ2) has a variable resistor that changes its value based on the concentration of gas that it contacts. If the gas has a high concentration, then the resistance decreases. If the concentration of the gas is low, then the resistance increases. It is necessary to add a resistor which acts as a load. This resistor will adjust the sensor's sensitivity. The value of this resistor can range from 2K Ω to 47K Ω . As this value increases, the more sensitive the sensor becomes. When the sensor detects a certain concentration of gas/smoke (abnormal value), it triggers an LED alarm as a visual indicator. The LED alarm provides a quick and visible alert to users indicating a possible fire. This gives a chance to people to take necessary precautions in the presence of hazardous gases. Its analog output will be read by the Arduino analog pin A0 to determine the concentration of gas in the atmosphere. The MQ2 Gas Sensor circuit diagram is shown in Figure 9.

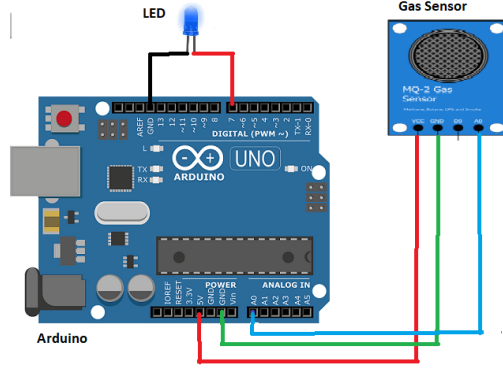


Figure 9. MQ2 gas sensor circuit diagram

IR Flame Sensor (REES52) is highly sensitive to infrared radiation, making it ideal for detecting flames. It uses infrared radiations emitted by flames to detect the presence of flames. The REES52 sensor converts this detection into a digital voltage signal, which is read by the Arduino at pin 7. When the signal exceeds a set threshold, the Arduino triggers a buzzer connected to pin 11 to provide an audible indication of the flame's presence. The audible buzzer serves as immediate indicator. The REES52 IR flame sensor circuit diagram is shown in Figure 10.

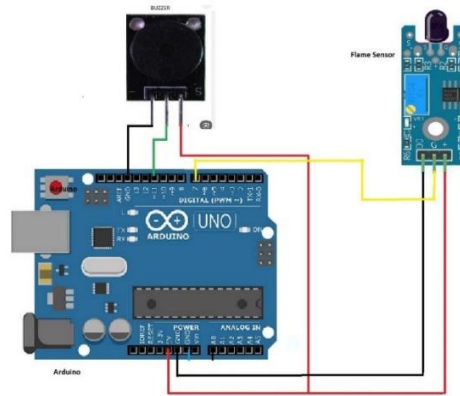


Figure 10. REES52 IR flame sensor circuit diagram

Temperature sensor (LM35) measures the temperature value and sends the data to the Arduino. This sensor will monitor the atmosphere temperature, triggering an alarm if it exceeds a predefined threshold. This is an indication of possible fire. The LM35 temperature sensor circuit diagram is shown in Figure 11.

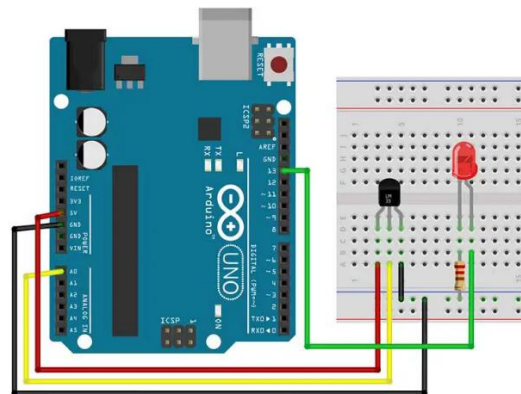


Figure 11. LM35 temperature sensor circuit diagram

The circuit diagram for the proposed intelligent vehicle safety system is presented in Figure 12. Now, when fire, gas, or abnormal value for temperature is detected, the Arduino activates the 5V relay, allowing the 12V battery to power the solenoid valve and water pump initiate the fire suppression process. That is, the Arduino reads all sensors, displays data on the LCD, and sends its commands to the LEDs, buzzer, GSM network, relay, solenoid, pump, and the SG90 servo motor. The LEDs will light up and buzzer will release audible signal. The GMS will

send an SMS message alerts during emergencies “FIRE/GAS DTECTED” to the mobile that is stored in the programming code. The relay will turn ON and activate Normally Open (NO) to control the solenoid valve. The solenoid gets magnetized and pulls the armature towards itself leaving the valve open. The Arduino activates a pump. The Arduino will send out PWM signals to the SG90 servo motor to rotate the spray nozzle toward the fire. Then the embedded board in the servo receives the signals through the signal pin and controls the direction of the fire suppression spray nozzle.

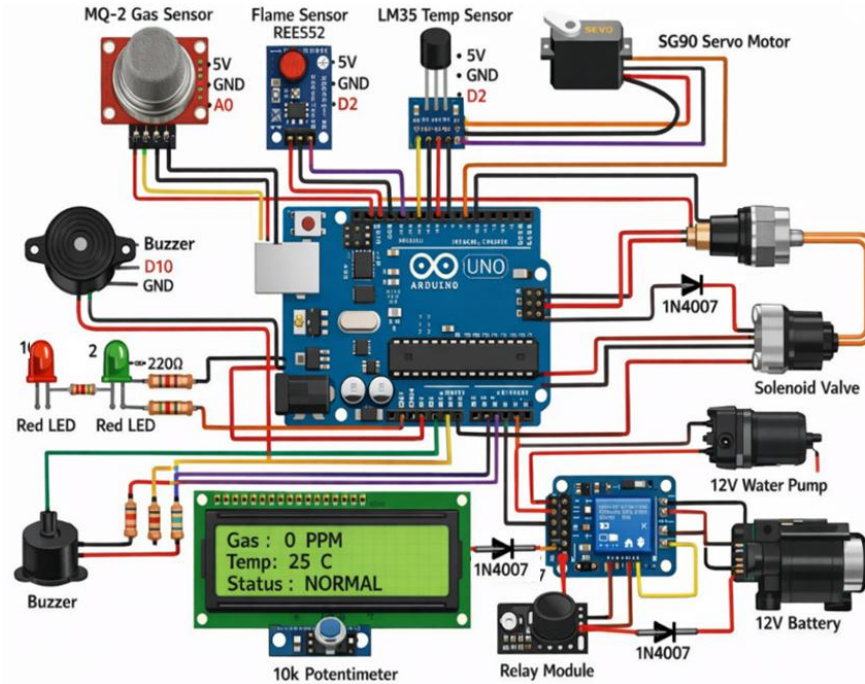


Figure 12. The circuit diagram for the proposed system

The diagram demonstrates the integration of sensing, processing, alerting, and actuation units, enabling early detection and effective suppression of fire and gas leakage in vehicular environments. The overall system operation is as follows. Sensors continuously monitor gas, flame, and temperature. Sensor data is sent to the Arduino controller. The Arduino evaluates the data against safety thresholds. Real-time data is displayed on the LCD. The code used to program the Arduino microcontroller was written using C++ programming language. If danger is detected:

- Buzzer is activated
- Red LED turns ON
- Relay switches ON (activates) the pump and solenoid
- Servo motor positions (rotates) the nozzle

Under normal conditions:

- Green LED remains ON
- Relay and pump remain OFF

Notice that sensors take 5V from Arduino, while pump and solenoid use external 12V battery.

Conclusion

The paper presented a comprehensive Arduino-based vehicle gas and fire detection and suppression system against one of the most dangerous vehicular hazards. This comprehensive vehicle safety system provides multi-layered protection against gas leaks, fires, and overheating and Automatic response without driver intervention. By integrating the MQ2 gas sensor, REES52 flame sensor, and LM35 temperature sensor for robust detection, and pairing them with an LCD, buzzer, LEDs for clear alerts, alongside an SG90 servo, relay, solenoid, and water pump for active suppression, the system offers a multi-layered approach to vehicle safety. The Arduino's

role as the central controller ensures seamless operation, making this design a practical and effective solution for enhancing vehicle safety against gas leaks and fires.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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Author(s) Information

Adnan M. Al-Smadi

Zarqa University, Department of Computer Science
Zarqa-Jordan
Yarmouk University, Department of Electronics Engineering
Irbid -Jordan
ORCID iD: <https://orcid.org/0000-0003-3796-6805>
*Contact e-mail: a.alsmadi@zu.edu.jo

Hazem Jihad Badarneh

Zarqa University, Department of Cyber Security
Zarqa-Jordan
ORCID iD: <https://orcid.org/0000-0002-1727-0758>

Ghadeer Zidan Sulieman

Al al-Bayt University, Department of Computer Science
Mafrq, Jordan
ORCID iD: <https://orcid.org/0009-0001-6462-2138>

*Corresponding author(s) contact email

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