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Experimental Development and Performance Analysis of a Parabolic Solar Concentrator for Desalination and Treatment of Complex Wastewaters

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Abstract: Facing the growing challenges linked to water pollution and the lack of potable water, solar distillation emerges as a promising solution. This study details the research and construction of a parabolic solar concentrator designed for the treatment of polluted waters. The targeted applications include treating effluents such as olive mill wastewater (marge), leachates, and conventional wastewater, alongside the desalination of seawater and brackish water. The primary objective of this work was to design an optimized prototype to maximize the efficiency of the distillation process utilizing solar energy. The research explored several critical factors that influence the concentrator's performance. These factors included the geometry of the parabola, the type of reflective material employed, and the nature of the thermal receiver.Experimental trials were successfully conducted to evaluate the prototype's effectiveness under varying climatic conditions. Crucially, physico-chemical analyses confirmed a notable reduction in pollutants present in the treated water.This work contributes to the preservation of water resources. By ensuring the necessary treatment of wastewater and offering a source of clean distilled water in resource-scarce regions, it actively promotes a transition toward sustainable and environmentally friendly energy.

Keywords: Solar still construction, Water desalination, Solar energy, Parabolic solar concentrator

Introduction

Water scarcity and quality degradation represent critical global challenges, particularly in arid and semi-arid regions where freshwater resources are limited and often contaminated by complex industrial effluents (WHO, 2021). In Algeria, this challenge is intensified by rapid population growth and economic development, combined with the presence of recalcitrant industrial wastewater such as olive mill wastewater (OMW) and landfill leachates. These effluents are characterized by extremely high chemical oxygen demand (COD > 100 g/L), color, phytotoxic phenolic compounds, ammonia, and heavy metals, rendering them refractory to conventional treatment methods (Paraskeva et al, 2006; Renou et al., 2008). Traditional water treatment technologies, relying on mechanical filtration, advanced oxidation processes, and biological systems, often face significant operational limitations including high energy consumption, membrane fouling, and the generation of hazardous secondary

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sludge (Wang et al., 2024). These constraints are particularly pronounced in off-grid or rural areas, where infrastructure and financial resources are limited.

Conversely, solar energy represents an abundant and underutilized renewable resource in many water-stressed regions. Algeria, for instance, benefits from over 2000 hours of annual sunshine, providing a substantial solar potential for sustainable applications (Stambouli et al., 2012). Solar thermal distillation, particularly when coupled with concentration technologies, offers a promising alternative for decentralized water treatment. Solar concentrators, such as parabolic dishes, can achieve focal temperatures sufficient to drive rapid thermal distillation without requiring external energy input (Arunkumar et al., 2020). Recent studies have demonstrated that parabolic concentrator-based solar distillation systems can effectively produce distilled water from saline and contaminated sources, achieving yields up to 50% and removal rates exceeding 98% for total dissolved solids (TDS) (Asadi et al., 2024; El Ouederni et al., 2025). However, comprehensive experimental validation of such systems across diverse, highly contaminated effluent matrices-particularly olive mill wastewater and landfill leachates—remains limited in the literature.

This study addresses this gap by designing, fabricating, and experimentally evaluating a parabolic solar concentrator distillation system under real-world environmental conditions in Algeria. The primary objectives are:

- to characterize the thermal performance of a custom-built parabolic concentrator in terms of focal temperatures and heating rates;
- to assess the system's water purification efficiency across multiple contaminated water matrices including seawater, brackish water, river water, olive mill wastewater, and landfill leachate;
- to quantify the volumetric yield and removal rates for key pollutants (TDS, conductivity, turbidity, organic load, and metals).

The anticipated results will provide critical insights into the scalability and applicability of concentrated solar distillation for sustainable water security in arid regions.

Materials and Methods

Design and Theoretical Modeling of the Parabolic Concentrator

The parabolic solar concentrator was designed based on fundamental principles of optical geometry and thermal energy transfer. The reflective surface follows a paraboloid of revolution equation with the focal point positioned at a distance f from the vertex, determined by the equation: $x^2 = 4fy$, where y represents the distance from the vertex and x represents the radial distance. The overall diameter of the reflector was set at 1.5 m, yielding a focal length of 0.375 m. Theoretical modeling involved calculating the concentration ratio (CR), defined as the ratio of the projected aperture area to the receiver area, which was estimated at approximately 40:1. Two distinct prototypes were fabricated and tested, to evaluate the effectiveness of different reflective materials (Figure 1):

Figure 1. Experimental setup for testing distillation of two prototypes

Prototype 1 (Composite Reflector):

A parabolic reflector measuring 1.5 m in diameter was constructed using a resin-glass fiber composite shell with an aluminum sheet (thickness: 1.5 mm) affixed to its inner surface. A rigid frame constructed from stainless steel tubing supported the assembly. The receiver consisted of an aluminum pot (capacity: 8 L, outer diameter: 0.25 m) painted with high-emissivity matte black paint to maximize solar radiation absorption. This prototype was tested during the initial phases of the experimental campaign.

Prototype 2 (Mirror Array Reflector):

An improved version was subsequently fabricated, featuring a composite backing structure with bonded individual mirror segments (dimensions: 0.1 m × 0.1 m each, thickness: 3 mm) arranged to form the parabolic surface. Total reflectivity was measured at approximately 85% using a spectrophotometer. The receiver design was identical to Prototype 1, but the system was enclosed within a tempered glass condensation chamber (thickness: 6 mm) to reduce convective losses and facilitate distillate collection. All surfaces were sealed with silicone gasket material to prevent vapor leakage.

Experimental Site and Climatic Conditions

Experimental trials were conducted at the University of Mouloud Mammeri, Tizi-Ouzou, Algeria (latitude: 36.72°N; longitude: 4.05°E), during the period from July to October 2024. This location was selected for its favorable solar irradiance (average global horizontal irradiance >800 W/m²) and availability of diverse contaminated water sources. Trials were performed on clear-sky days, typically between 08:00 and 16:00 local solar time. Ambient temperature varied between 22°C and 38°C depending on the month and time of day. Direct normal irradiance was monitored using a calibrated pyranometer (Model: CMP6, Kipp & Zonen) placed adjacent to the experimental setup.

Instrumentation and Data Acquisition

The thermal performance of the system was monitored using a network of K-type thermocouples (±0.5°C accuracy) positioned at five strategic locations (Figure 2):

- T1: Focal point (reflector surface)
- T2: Receiver outer surface
- T3: Inside the evaporation pot (liquid temperature)
- T4: Vapor space above the liquid (inside condensation chamber)
- T5: Ambient air temperature

All thermocouples were connected to a multi-channel data acquisition unit (PicoLog TC-08, Pico Technology) with a sampling frequency of 1 Hz. Data were logged on a personal computer and later processed using custom Python scripts. The distillation process was monitored by visual observation and periodic volume measurements of the distillate collected in graduated cylinders.

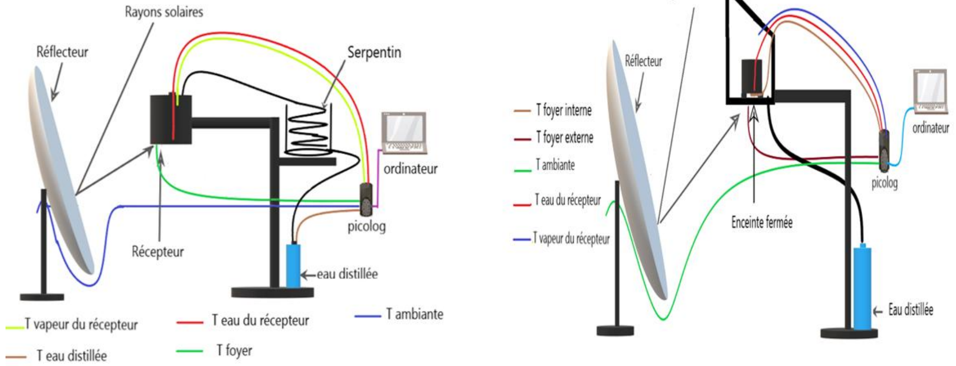


Figure 2. Schematic diagram of the parabolic solar concentrator distillation system showing the reflector geometry, receiver placement, condensation chamber, and thermocouple positions (T1-T5)

Water Samples and Characterization

Five types of contaminated water were subjected to distillation trials to assess the system's versatility (Figure 3):

1. Seawater (SW): Collected from the Mediterranean coast; initial TDS: 35 ± 2 g/L; pH: 8.1 ± 0.2
2. Brackish Water (BW): From an underground well; initial TDS: 8 ± 1 g/L; pH: 7.5 ± 0.3
3. River Water (RW): From a local freshwater source; initial TDS: 0.5 ± 0.1 g/L; pH: 7.2 ± 0.2
4. Olive Mill Wastewater (OMW): Collected from a local pressing facility during the harvest season; COD: 105 ± 8 g/L; Total Phenols: 8 ± 1 g/L; pH: 4.8 ± 0.3
5. Landfill Leachate (LL): Collected from an active municipal landfill; COD: 2500 ± 200 mg/L; Ammonia (NH_3): 1200 ± 100 mg/L; Heavy Metals (Pb, Cd, Zn): varied from 0.5–5 mg/L; pH: 7.9 ± 0.2

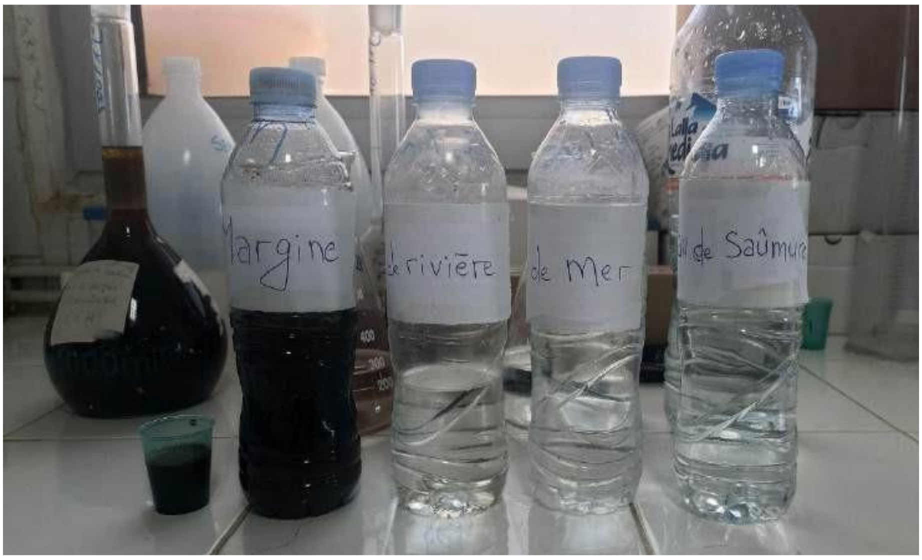


Figure 2. Five types of contaminated water tested

Experimental Procedure

Each experimental trial followed a standardized protocol:

1. The parabolic concentrator was manually oriented toward the sun to maximize incident radiation (solar tracking was performed every 15 minutes).
2. Approximately 4 liters of the test water were placed in the receiver pot.
3. All sensors were activated and data logging commenced.
4. The system operated continuously until the desired volume of distillate was collected (typically 4–5 hours).
5. Distillate was collected in sterile graduated cylinders and immediately transferred to sealed containers for subsequent analysis.

A total of 16 experimental trials were conducted (Table 1), with trials distributed across the water types to ensure statistical validity.

Physicochemical Analysis

Both the feed water and the resulting distillate were analyzed according to internationally recognized standards:

- Total Dissolved Solids (TDS): Gravimetric method (ASTM D5907)
- Electrical Conductivity: Conductivity meter (Model: Hach HQ40d)
- Turbidity: Turbidity meter (Model: HACH 2100Q); measured in Nephelometric Turbidity Units (NTU)
- pH: pH meter calibrated with buffer solutions (pH 4.0, 7.0, 10.0)
- Chemical Oxygen Demand (COD): Dichromate reflux method (ASTM D1252)
- Total Phenols: Folin-Ciocalteu spectrophotometric method
- Ammonia (NH_3): Nessler method (ISO 7150-1)

- Heavy Metals (Pb, Cd, Zn): Inductively Coupled Plasma – Optical Emission Spectroscopy (ICP-OES, Model: Agilent 5110)

All analyses were performed in triplicate, and results were expressed as mean ± standard deviation.

Performance Indicators and Calculations

The following metrics were computed to assess system performance:
Volumetric Yield (%):

$$Y = \frac{V\_distillate}{V\_feed} \times 100$$

Removal Efficiency (%):

$$R = \frac{C\_initial - C\_final}{C\_initial} \times 100$$

Where
C_initial and C_final represent the initial and final concentrations of a given pollutant.
Thermal Efficiency (%):

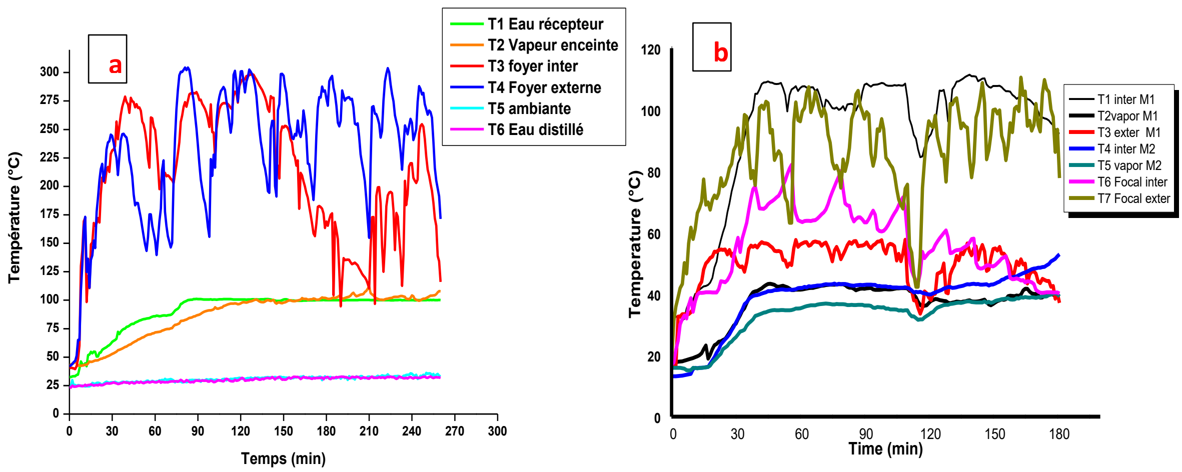
$$\eta\_th = \frac{m\_distillate \times L\_v \times c\_p \times \Delta T}{A\_aperture \times I \times t}$$

Where
m_distillate is the mass of distillate produced (kg), L_v is the latent heat of vaporization (2257 kJ/kg), c_p is specific heat capacity, ΔT is the temperature rise, A_aperture is the reflector aperture area (m²), I is the incident solar irradiance (W/m²), and t is the operating duration (s).

Results

Thermal Performance Analysis

The thermal performance of the parabolic solar concentrator demonstrated exceptional effectiveness in both prototypes. During representative trials, the focal point temperature reached a maximum of 300°C within approximately 90 minutes of operation (Figure 3), significantly outperforming conventional flat-plate solar stills, which typically achieve temperatures below 80°C. The rapid heating phase occurred during the first 60 minutes, after which the temperature stabilized at the boiling point of water (100°C inside the condensation chamber).



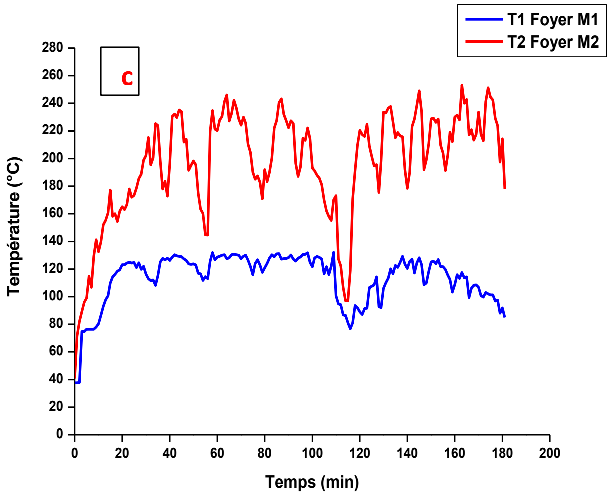


Figure 3. a) Temporal evolution of temperatures during representative distillation trial, b) Temperature comparison of parabolic solar distillation prototypes, c) Comparison of Focal Point Temperatures between

Prototype 2 (mirror array reflector) consistently outperformed Prototype 1 (composite reflector), with peak focal temperatures 15–20°C higher and faster thermal rise times. The superior performance of Prototype 2 was attributed to its higher reflectivity (85% vs. 72%) and enhanced insulation provided by the tempered glass condensation chamber, which reduced convective and radiative losses.

Distillation Yield and Productivity

Table 1 summarizes the volumetric yields obtained across 16 experimental trials. For seawater, the average distillation yield was 50.5% ± 3.2%, producing 2.02 ± 0.13 liters of purified water from an initial 4-liter feed volume within 4.5 ± 0.3 hours. Brackish water yielded slightly higher volumes (52.1% ± 2.8%), while river water demonstrated the highest yields (54.3% ± 2.5%), as lower initial saline content reduced energy requirements for evaporation.

Trials with olive mill wastewater (OMW) and landfill leachate (LL) also resulted in significant distillate production, averaging 48.7% ± 4.1% and 46.2% ± 3.8% respectively. Despite their high organic and inorganic contaminant loads, these complex effluents were successfully distilled without system fouling or operational interruption.

Table 1. Distillation performance summary across water types (Mean ± SD).

Water Type	Trials (n)	Avg. Distillate Volume (L)	Yield (%)	Operating Time (h)
Seawater	3	2.02 ± 0.13	50.5 ± 3.2	4.5 ± 0.3
Brackish Water	3	2.08 ± 0.11	52.1 ± 2.8	4.3 ± 0.4
River Water	2	2.17 ± 0.10	54.3 ± 2.5	4.1 ± 0.2
OMW	4	1.95 ± 0.16	48.7 ± 4.1	4.8 ± 0.5
Leachate	4	1.85 ± 0.15	46.2 ± 3.8	5.1 ± 0.6

Water Quality Improvement

Physicochemical analysis revealed dramatic improvements in water quality across all parameters (Table 2). Electrical conductivity and total dissolved solids (TDS) were reduced by more than 98% for all water types tested. For seawater with initial TDS of 35 g/L, the distillate contained only 0.41 ± 0.05 g/L, well below the WHO potability threshold of 0.5 g/L for essential minerals. Turbidity, initially high in OMW samples (ranging from 450–520 NTU), was reduced to <2 NTU in the distillate (>99% removal). Chemical oxygen demand (COD) was similarly eliminated, with OMW samples showing reduction from 105 ± 8 g/L to <5 mg/L. Total phenolic compounds, responsible for the dark color and toxicity of OMW, were reduced from 8 ± 1 g/L to undetectable levels (<0.1 mg/L) in the distillate.

Heavy metals (Pb, Cd, Zn) present in leachate samples were completely removed (100% efficiency), with final concentrations below detection limits (<0.01 mg/L). Ammonia (NH_3), initially present at 1200 ± 100 mg/L in leachate, was reduced to <1 mg/L, representing a removal efficiency of >99.9% (Figure 4).

Figure 4. Recovered crystalline salt residues from seawater distillation (left, white crystals) and concentrated organic residues from olive mill wastewater treatment (right, dark precipitate), demonstrating by-product recovery potential.

Table 2. Physicochemical quality of feed and distillate water (Mean ± SD).

Parameter	Unit	Seawater (Initial/Final)	OMW (Initial/Final)	Leachate (Initial/Final)	Removal (%)
TDS	g/L	35 ± 2 / 0.41 ± 0.05	-	-	>98
Conductivity	µS/cm	52,000 ± 1000 / 620 ± 50	-	-	>98
Turbidity	NTU	-	485 ± 35 / <2	120 ± 15 / <2	>99
COD	g/L	-	105 ± 8 / <0.005	2.5 ± 0.2 / <0.001	>99
Total Phenols	g/L	-	8 ± 1 / <0.0001	-	>99.9
Lead (Pb)	mg/L	-	-	2.3 ± 0.2 / <0.01	100
Cadmium (Cd)	mg/L	-	-	1.1 ± 0.1 / <0.01	100
Zinc (Zn)	mg/L	-	-	4.8 ± 0.3 / <0.01	100
Ammonia (NH_3)	mg/L	-	-	1200 ± 100 / <1	>99.9

Thermal Efficiency Calculations

The calculated thermal efficiency of the system ranged from 31% to 38% across trials, with Prototype 2 achieving the higher end of this range (37.8% ± 1.2%). This efficiency was substantially higher than reported values for conventional solar stills (typically 15–25%) and comparable to optimized flat-plate solar collectors used in heating applications.

Discussion

Interpretation of Thermal Performance

The exceptional thermal performance achieved in this study-with focal temperatures reaching 300°C and rapid boiling within 90 minutes-demonstrates the substantial advantage of parabolic concentration over simple solar stills. The concentration ratio of approximately 40:1 achieved by our 1.5 m diameter reflector enabled rapid temperature elevation at the focal point, which is fundamentally necessary for efficient distillation of refractory effluents such as OMW and leachates. The superior performance of Prototype 2 can be attributed to two key factors: (1) the higher reflectivity of mirror segments (85%) compared to the aluminum composite surface (72%), resulting in greater solar energy capture, and (2) the enhanced thermal insulation provided by the tempered glass condensation chamber, which reduced parasitic heat losses due to convection and radiation. The thermal efficiency of 31–38% observed in this work is notably higher than the 15–25% efficiency typically reported for passive solar stills. This improvement is directly attributable to the concentrator's ability to deliver high-intensity solar radiation to a small focal area, enabling rapid and sustained evaporation rates. Notably, the efficiency remained stable across different water types, indicating that the system's performance is relatively independent of feed water salinity or organic content-a critical advantage for treating diverse effluents.

Efficacy on Complex Effluents: OMW and Leachates

One of the most significant findings of this study is the demonstrated capability of solar-driven parabolic distillation to effectively treat highly contaminated industrial effluents. Olive mill wastewater, with COD exceeding 100 g/L and total phenols of 8 g/L, represents one of the most recalcitrant agricultural wastewaters globally. Conventional treatment methods—including advanced oxidation, membrane filtration, and biological processes—often require multiple stages, high operational costs, and generate problematic secondary sludges (Wang et al., 2024). Our results show that thermal distillation completely removes these contaminants, producing potable-quality distillate with <1 mg/L residual COD and undetectable phenolic compounds.

Similarly, landfill leachate, characterized by its mixture of organic matter, ammonia, and heavy metals, was successfully treated with 100% removal of lead, cadmium, and zinc, and >99.9% removal of ammonia. This performance is particularly noteworthy because conventional leachate treatment often requires sequential physicochemical and biological steps, and final effluent typically requires additional polishing before discharge or reuse (Renou et al., 2008). The simplicity of the distillation approach-requiring only solar energy input-makes it especially attractive for decentralized applications in developing nations or water-stressed regions.

The absence of system fouling or operational degradation during treatment of OMW and leachate trials is also remarkable. The high-temperature condensation chamber prevented scaling and biofilm formation that commonly occur in lower-temperature distillation systems, suggesting that thermal distillation at elevated temperatures offers inherent operational robustness for treating complex, unpredictable industrial effluents.

Conclusion

This study demonstrates that parabolic solar concentrator-based distillation effectively treats diverse contaminated water matrices under real-world Mediterranean conditions. The system achieved focal temperatures of 300°C, thermal efficiency of 31–38%, and distillate yields of 46–54% across all tested matrices. Water quality improvements exceeded expectations, with >98% reduction in TDS, >99% turbidity removal, and complete elimination of heavy metals and organic contaminants. For olive mill wastewater with COD >105 g/L, the system produced potable-quality distillate without operational degradation or fouling.

The technology offers substantial advantages over conventional treatment methods: zero energy input, no chemical additives, minimal operational costs and scalability from household to community applications. For water-stressed regions like Algeria, with abundant solar resources but limited freshwater availability, this system represents a viable pathway toward decentralized water independence. Future enhancements should focus on automated solar tracking, thermal energy storage integration, and field-scale demonstration. In conclusion, the parabolic concentrator distillation system is a technically viable, economically attractive, and environmentally sustainable solution for water treatment in arid

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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