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Original Research

High-Desalination-Performance Solar Still With a Sustainable Carbonaceous Biopolymer as a Photothermal Interface

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Abstract

Background: Conventional solar stills (CSS) suffer from low thermal efficiency and limited freshwater output. To overcome this limitation, this study investigates a sustainable and cost-effective performance optimization technique using local carbonaceous waste. Specifically, variable-thickness layers of plant tar are utilized as a biostructured, photothermal material to enhance heat retention at the water surface and boost desalination performance in arid regions like El Oued, Algeria. **Methods:** An experimental comparative analysis was conducted between a CSS and modified solar stills equipped with plant tar layers of varying thicknesses. The evaluation monitored daily freshwater productivity and thermal efficiency under identical local meteorological conditions. Furthermore, a comprehensive economic viability assessment was performed to calculate fabrication costs and payback periods. **Results:** The modified stills demonstrated significantly superior performance, delivering freshwater productivities of 1.35 L/day, 1.44 L/day, 1.49 L/day, and 1.56 L/day (at a 1.00 cm thickness), outperforming the CSS (1.00 L/day) by 35%, 43.8%, 49%, and 56%, respectively. Thermal efficiency followed a matching trend, peaking at the 1.00 cm coating thickness due to optimal heat localization. Economically, although the modified stills have slightly higher fabrication costs compared to the CSS 12,550 DA(USD 96.90). 11,300 DA(USD 87.21), they prove highly profitable, recouping the initial investment in just 2.74 months (82 days) compared to nearly 4 months for the CSS. **Conclusions:** This study demonstrates that local carbonaceous waste can be efficiently valorized as a high-performance photothermal material for solar distillation. The proposed system offers a highly profitable, sustainable, and accessible solution for supplying drinking water to populations in arid zones, directly contributing to the achievement of Sustainable Development Goal 6 (SDG 6).

Keywords: photothermal conversion; carbonaceous biopolymer; vegetable tar; interfacial evaporation; development economics; frugal innovation; water security; solar distillation

1. Introduction

The thermochemical conversion of biomass and carbonaceous resources is a vital process for generating sustainable energy carriers. A primary liquid byproduct of this conversion is tar, formed through complex radical condensation and cracking reactions during pyrolysis [1]. Beyond its industrial challenges, tar is recognized as a dense reservoir of high-value aromatic compounds and chemicals recoverable through advanced thermochemical pathways [2]. Recovery efficiency can be further enhanced by optimizing reactor dynamics; for example, specific particle geometries influence temperature distribution and regulate the resulting tar yield [3]. Practical utilization of these high-energy byproducts requires effective management and purification. Recent engineering advances have introduced integrated cooling and cleaning systems, such as vegetable oil bubblers, achieving tar reduction efficiencies exceeding 98% [4]. Furthermore, machine learning has emerged as a transformative methodology for predicting the energy content and hydrogen yield of tar-derived products [5]. Finally, evaluations of novel gasification stages demonstrate that controlling variables like the steam-to-biomass ratio minimizes problematic tar fractions while ensuring the production of usable gas from low-quality feedstocks [6].

To address the productivity limitations of conventional solar stills (CSS), researchers have explored high-conductivity metallic components and structural modifications. Using black-coated machining metal scrap as a photothermal absorber demonstrated a 129.85% increase in potable water yield and reduced the payback period to 5.4 months [7]. Further enhancements were achieved via stepped basins with copper fins; results indicate that a +30° fin angle combined with optimized flow rates can achieve a 171% efficiency increase [8]. In complex thermal systems, encapsulated open-cell copper metal foam embedded in nano-enhanced phase change materials (nPCM) boosted exergy efficiency by 64.2% [9]. Innovative absorber designs, such as steel egg trays combined with desert crystalline sand roses and conical ring reflectors, reached daily yields of 14.7 L/m^2, a 253.37% improvement over classical designs [10]. Localized experimental work in the El Oued region confirms that structural iron rods with 0 cm spacing modified solar still (MSS) can raise peak water temperatures to 60 °C and cumulative output to 740 mL, substantially exceeding the 600 mL produced by a CSS [11]. Moreover, hemispherical solar stills have been shown to outperform simple square absorbers by 54.30% in pure water output [12].

Parallel to metallic modifications, chemical and synthetic additives have emerged as high-performance strategies. Metallic and metal-oxide nanoparticles, such as Ag, Au, and TiO_2 at 0.1 wt%, dispersed in black paint achieved thermal efficiency improvements of 38.2% [13]. Spinel-structured nanoparticle coatings on perforated SS304 plates reached peak efficiencies of 40.9% and yields of 2.1 L/day [14]. Other chemical approaches focus on the photocatalytic effects of oxides like CuO, Fe_2O_3, and ZnO, where a 0.16 wt% concentration of CuO increased productivity by 22.43% [15]. Advanced thermal management using CuO nanofluids in glass tubes demonstrated a 66.67% increase in yield and an 85.7% improvement in efficiency [16]. Beyond additives, physical chemical properties such as surface tension have been manipulated using 0.5 cm diameter plastic fin tubes, increasing evaporation rates by 41.4% [17]. Additionally, the integration of hybrid nano-enhanced PCM with black sand and sponges achieved an 81.89% reduction in the cost-per-liter of distilled water [18].

The modern research landscape is shifting toward sustainable, recovery-based materials. Minerals derived from natural black sand have shown potential as sustainable alternatives to synthetic nanofluids, increasing freshwater production by 80.96% when combined with glass cooling and reaching a 102% enhancement in exergy efficiency [19]. Waste-derived materials, such as floating coal and cotton fabrics combined with carbon black nanoparticles, reached a 142.7% increase in exergy efficiency by emphasizing the capillarity effect [20]. Regarding bio-waste, integrating olive and date kernels at 500 g/5 L improved cumulative water production by 226% and 176%, respectively [21]. Other sustainable additives, such as blue metal stones, produced 1.5 times as much drinkable water as pebble stones [22]. Furthermore, cellulose cardboard and sponge pieces enhanced performance by 19.8% and 10% in conventional designs [23,24]. Most recently, hydrogel evaporators incorporating coal tar pitch porous carbon achieved a light-to-heat conversion rate of 1.44 kg/(m^2·h) under 1 sun, demonstrating the potential for carbonaceous byproducts to facilitate efficient solar-driven water purification [25].

Recent trends in solar desalination have shifted toward the valorization of waste materials, aligning with circular economy principles. For instance, carbonized custard apple seeds increased distillate yield by 115.5%, reaching 4.88 L/day [26]. Similarly, coastal waste like clam shells improved output by 90.54% through sensible heat storage [27], while incorporating agricultural waste microparticles into PCMs resulted in a 126.4% enhancement in yield [28]. Beyond agricultural waste, integrating recycled aluminum cans with beeswax achieved a thermal efficiency of 60% [29], and composite materials derived from waste salt improved thermal conductivity by 15.8% [30]. Furthermore, food industry waste integration into solar fuel systems has achieved solar-to-fuel performances of up to 44%, highlighting waste-to-energy potential [31].

Despite these global advancements, the utilization of waste-derived biopolymers as functional evaporation interfaces remains a nascent field. This study addresses this gap by introducing natural vegetable tar as a sustainable, carbon-based bio-structure for solar still basins. Moving beyond expensive, conventional absorbers, this local resource aligns with the principles of frugal innovation to provide a zero-cost solution for decentralized water systems. The primary objective of this investigation is to evaluate the impact of bio-coating thickness on photothermal conversion and evaporation kinetics. Specifically, the research analyzes how the morphological evolution of the tar layer influences the thermal gradient between the absorber surface and the glass cover. Furthermore, a development economics framework is applied to assess the financial viability of this bio-based technology, ensuring a high-performance desalination solution remains accessible for marginalized communities in arid and semi-arid regions.

2. Materials and Methods

2.1 Material Selection: Vegetable Tar as a Biopolymeric Absorber

Vegetable tar is a natural, plant-based substance found easily in local Algerian markets at a low cost. Traditionally, it is used for medicine or as a coating for clay water-storage pots. This study adapts that traditional use by applying it to solar distillation. Because the tar naturally absorbs thermal energy and is already used for drinking water storage, it is a safe and effective way to boost still performance.

Using this local material provides a sustainable way to produce clean water without needing expensive, imported parts. The tar acts as a carbon-rich layer that traps solar radiation. The vegetable tar utilized in this study is a complex carbon-rich biopolymer obtained through the thermal decomposition of local biomass. The intense black coloration (Table 1) indicates a high extinction coefficient for solar radiation. Most importantly, its low thermal conductivity (approx. 0.15 W/m-·K) allows it to function as a selective absorber that localizes thermal energy at the surface, a behavior typical of porous carbonaceous materials.

Table 1. **Physical and thermophysical characterization of the vegetable tar coating**.

Property	Characteristic	Value/Description	Significance for photothermal conversion
Physical	Appearance & Color	Intense Black/Opaque	High solar absorptivity across the visible spectrum.
Chemical	Nature	Carbon-rich Biopolymer	Derived from wood pyrolysis; naturally contains carbonaceous structures.
Mechanical	Kinematic Viscosity	100–450 mm^2/s (at 40–80 °C)	Ensures stable, uniform adhesion to surfaces during thermal cycling.
Thermal	Conductivity	0.151–0.159 W/m·K	Acts as a thermal insulator to prevent heat loss to the substrate.
Thermal	Density	1056–1083 kg/m^3	Provides moderate thermal mass for energy storage.

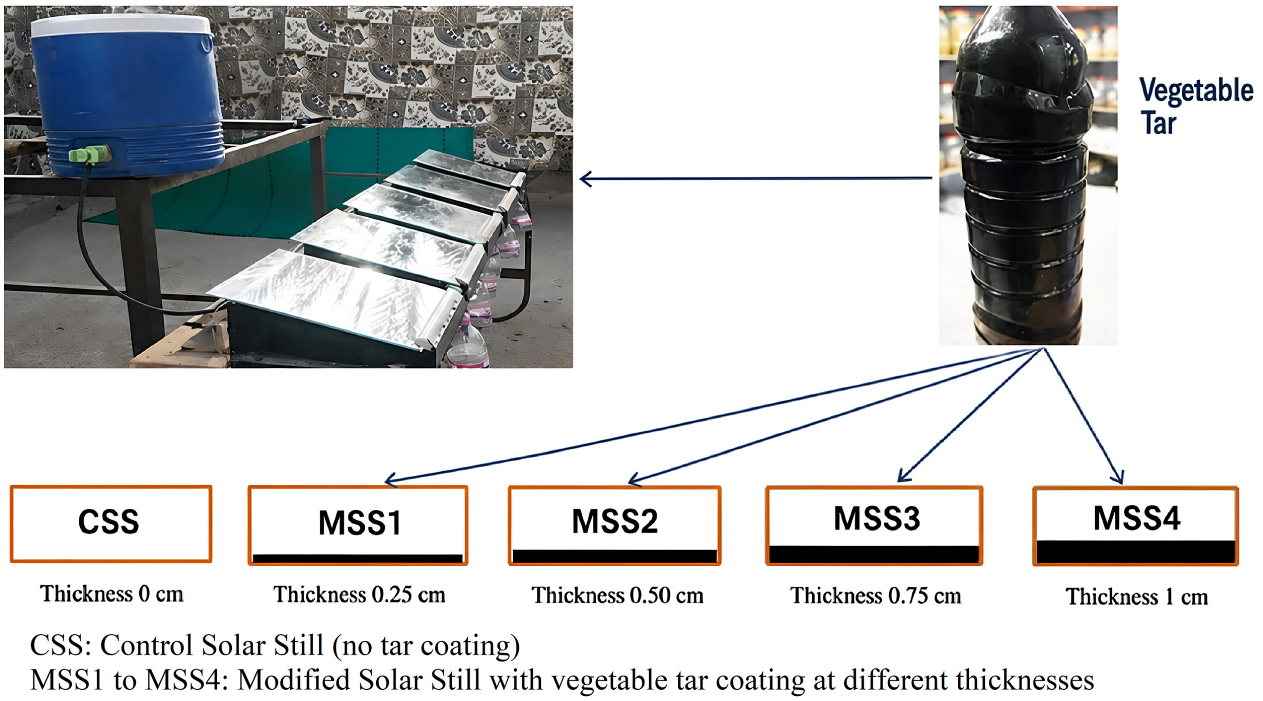

Fig. 1. Solar stills installation.

2.2 Experimental Procedure and System Configuration

Testing took place at the University of El Oued in May 2025. To ensure a fair comparison, the setup included five identical solar stills running at the same time under the same outdoor conditions. As shown in Fig. 1, one unit was a CSS used as a baseline. The other four units MSS1, MSS2, MSS3, and MSS4 were modified with vegetable tar coatings at thicknesses of 0.25 cm, 0.50 cm, 0.75 cm, and 1.00 cm, respectively.

The goal of adding the vegetable tar was to act as a heat-absorbing layer to improve thermal transfer. By trapping heat right at the water's surface, the system reduces the energy lost to the rest of the water volume. To track how well these modifications worked, K-type thermocouples were placed to monitor the temperature of the basin water (T_w), the ambient temperature (T_{amb}), and the inner glass covers (T_{gi}). Solar intensity was recorded using a pyranometer, while the distillate yield was measured hourly using graduated cylinders. All instruments were calibrated beforehand to ensure the data was accurate and were characterized by the uncertainties listed in Table 2.

To ensure a uniform coating thickness (0.25–1.00 cm), the solar still basins were first leveled using a precision spirit level, followed by the incremental application of vegetable tar which was manually verified at multiple reference points using a calibrated depth gauge to match pre-calculated volume requirements.

3. Results

3.1 Sunlight and Outside Temperature

Fig. 2 shows how the solar intensity and the outside temperature changed during the test day. As expected, the sun's radiation climbed steadily throughout the morning, hitting a peak of 1009 W/m^2 between 12:00 and 14:00.

The air temperature followed this same pattern closely. The highest ambient temperature of 50 °C was measured at 14:00, right after the solar peak. This close link shows how much the local weather in El Oued depends on direct sunlight. Both the radiation and the temperature stayed high during the solar noon period before dropping off toward the evening as the sun went down. This data confirms that the environmental conditions were consistent and strong enough for high-performance distillation.

Table 2. Technical specifications and accuracy of the measuring instruments.

Instrument	Measuring device used	Measured parameter	Accuracy	Uncertainty
K-type thermocouples	Model: UT139 Serie, UNI-TREND Technology Co., Ltd. Dalian, Liaoning, China	T_w, T_{gi}, T_{amb}	± 0.1 °C	0.5%
Solar pyranometer	Model: 4890.20, Frederiksen Scientific A/S, Ølgod, Denmark	Global solar radiation	± 10 W/m^2	2.5%
Graduated cylinder	-	Hourly and daily yield	± 5 mL	1.5%

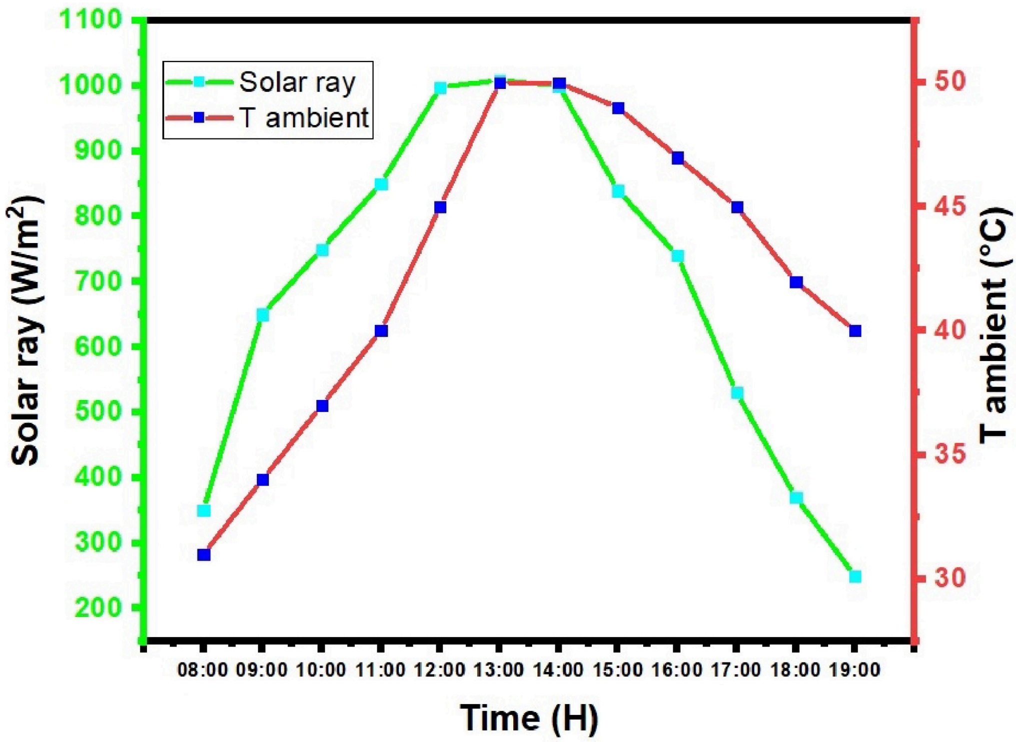

Fig. 2. Hourly variation of solar irradiance and ambient temperature.

3.2 Glass Cover Internal Temperature

Fig. 3 compares the temperature changes on the inner surface of the glass cover for all five solar stills. The data shows a clear difference between the CSS and the four modified units (MSS1–MSS4). While every unit followed the same general path heating up in the early afternoon and cooling down toward the evening—the modified stills consistently reached higher temperatures.

The standard still hit a maximum of 56 °C. In contrast, the modified setups reached higher peaks: 58 °C for MSS1, 59 °C for MSS2, 60 °C for MSS3, and 62 °C for MSS4. This temperature boost comes from the vegetable tar coating. Because the tar is an effective absorber, it harvests more solar radiation and keeps the heat localized at the water's surface. This increased energy then moves to the glass through convection and evaporation, raising the glass temperature. The effect is strongest with the 1.00 cm layer (MSS4), which appears to be the best thickness for maintaining high thermal levels.

The energy balance for the inner face of the glass cover, which includes radiation, convection, and evaporation from the water to the glass, is expressed by the following Eqn. (1) [16]:

$$\frac{M_g \mathrm{Cp}_g}{A_g}\frac{dT_{gi}}{dt} = Q_{r.w\_gi} + Q_{c.w\_gi} + Q_{evap} - Q_{c.gi\_ge} \quad (1)$$

3.3 Evolution of Water Temperature

Fig. 4 shows how the water temperature in the basin changed for both the standard (CSS) and modified (MSS) solar stills. The data indicates a clear difference in temperature among the five setups. Every system followed the same daily heating cycle: temperatures climbed during the morning, hit their peak in the early afternoon, and then dropped toward the evening. The biggest gap between the stills happened between 13:00 and 15:00, when the sun was strongest.

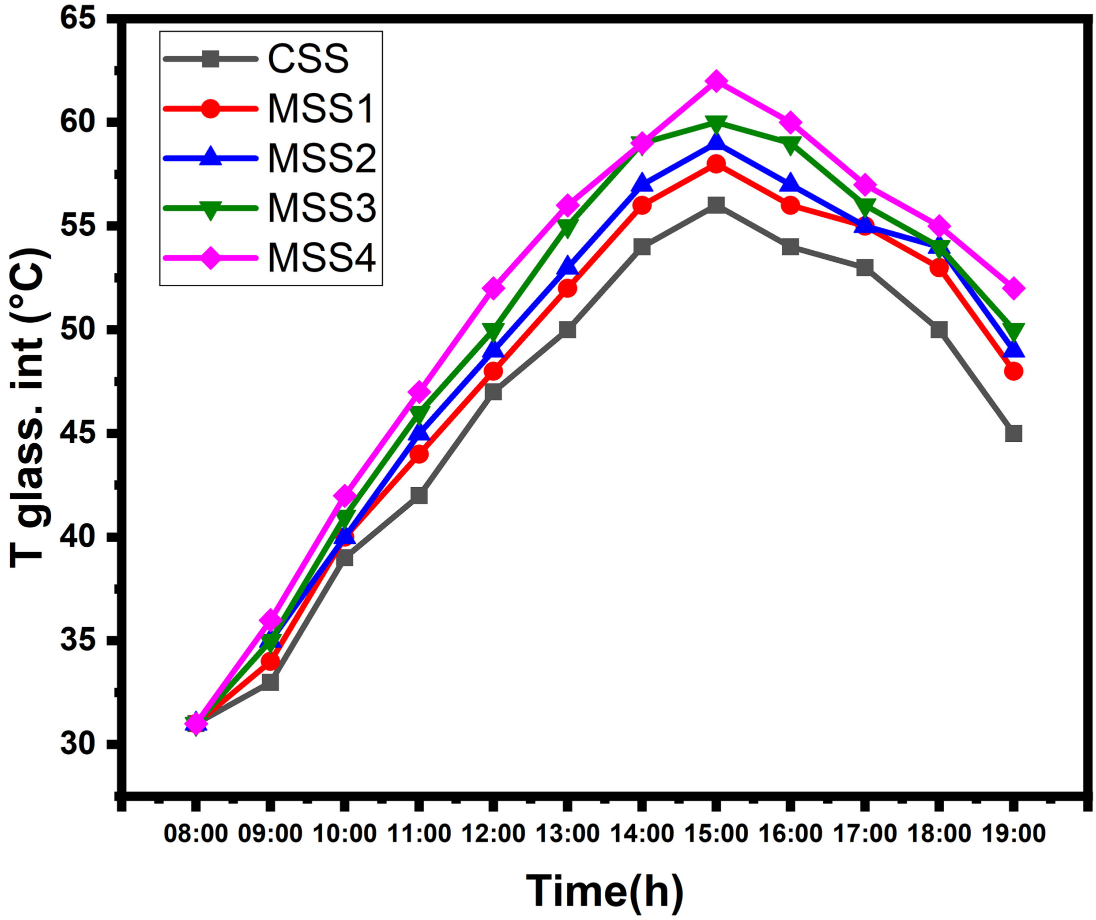

Fig. 3. Glass cover internal temperature.

The CSS reached a maximum water temperature of 69 °C. In comparison, the modified units hit higher peaks: 72 °C for MSS1, 73 °C for MSS2, 74 °C for MSS3, and a maximum of 76 °C for MSS4. This improvement is due to the vegetable tar layer. By acting as a heat-trapping interface, the tar captures solar radiation and keeps the thermal energy right at the water's surface. This "interfacial heating" prevents heat from being wasted in the rest of the water volume, which speeds up the evaporation process. The 1.00 cm thickness in MSS4 proved to be the best for absorbing and holding heat effectively.

The energy balance for the basin water, which tracks how much heat is stored compared to the solar gain and losses to the glass and basin walls, is expressed as follows [16]:

$$\frac{M_w \mathrm{Cp}_w}{A_w}\frac{dT_w}{dt} = \alpha_w \tau_g G + Q_{c.b.\_w} - Q_{c.w.\_g} - Q_{evap} - Q_{r.w.\_g.i} \quad (2)$$

3.4 Hourly Pure Water Yield

Fig. 5 shows the hourly water production for the modified stills (MSS1–MSS4) compared to the standard CSS. The data shows that using vegetable tar consistently results in a higher water output at every hour of the day. For all setups, the production followed a parabolic curve: it started low in the morning, peaked in the afternoon, and then dropped as the sun went down.

The highest hourly production for every unit happened at 15:00. This is slightly after the sun was at its strongest, a delay caused by the time it takes for the basin water to heat up (thermal inertia). The CSS reached a peak of 0.60 $L/m^2 \cdot h$ (150 mL), while the modified stills produced much more: 0.64 $L/m^2 \cdot h$ (160 mL) for MSS1, 0.74 $L/m^2 \cdot h$ (185 mL) for MSS2, 0.76 $L/m^2 \cdot h$ (190 mL) for (MSS3), and a maximum of 0.80 $L/m^2 \cdot h$ (200 mL) for MSS4.

This difference in water flow is a direct result of the biopolymeric interface. The vegetable tar does more than just soak up heat; its structure speeds up the evaporation process at the water's surface. By trapping thermal energy right where the air meets the water, the tar lowers the amount of energy needed to turn the water into vapor. The 1.00 cm thickness in MSS4 provides the best surface for

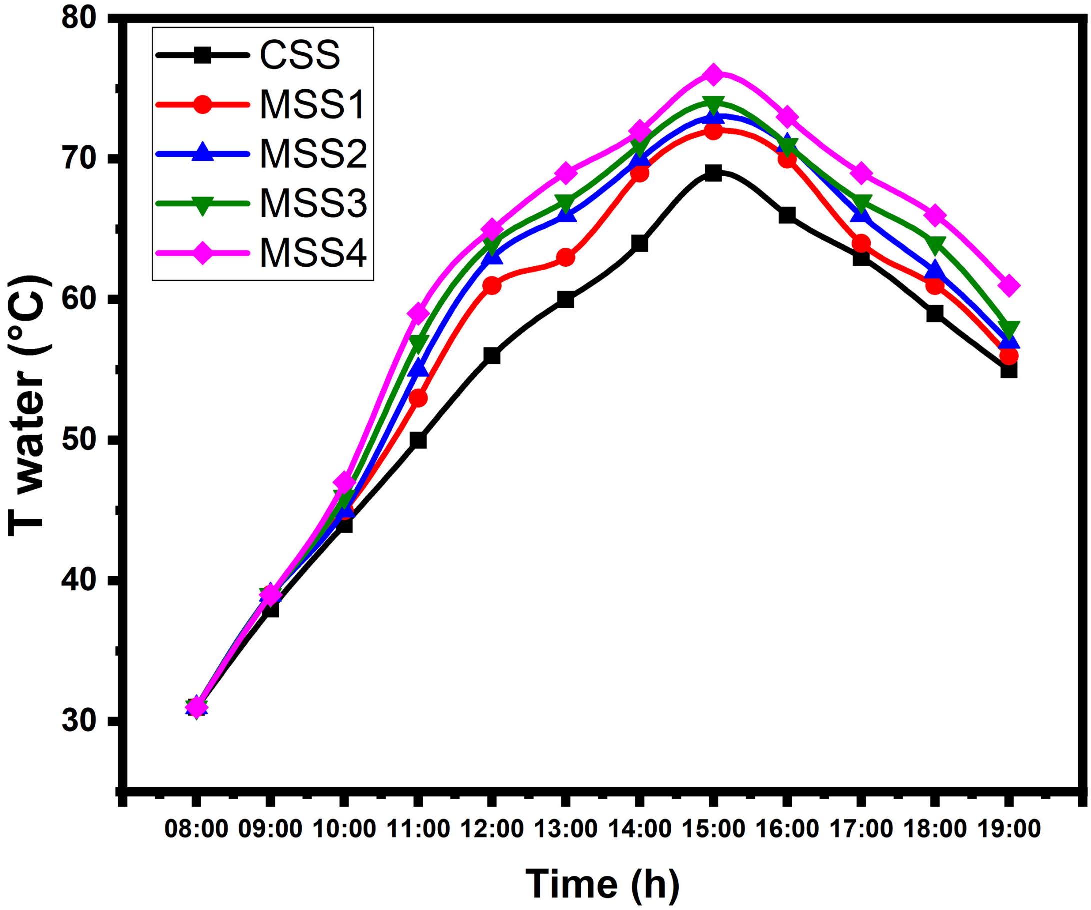

Fig. 4. Water temperature evolution.

this heat conversion, which increases the vapor pressure and leads to more condensation on the glass. These results prove that moving from a flat basin to a biostructured absorber is a key way to get high-efficiency distillation.

3.5 Total Pure Water Accumulation

Fig. 6 shows the total water collected for both the standard (CSS) and modified (MSS1–MSS4) solar stills over the course of the experiment. The results show a steady, linear increase in water output for all setups as the day went on. The performance gap between the units became much more obvious in the afternoon. A key finding is the significant enhancement in distillate yield attributed to the biopolymeric interface. The CSS achieved a daily productivity of 1.00 L/day (corresponding to a cumulative yield of 4.00 L/m^2 day). In comparison, the modified units delivered substantially higher yields: 1.35 L/day (5.40 L/m^2·day) for MSS1, 1.44 L/day (5.75 L/m^2·day) for MSS2, 1.49 L/day (5.96 L/m^2·day) for MSS3, and a maximum of 1.56 L/day (6.24 L/m^2·day) for MSS4. This represents a 56% increase in total freshwater production for the optimal 1.00 cm tar setup relative to the conventional reference.

This higher accumulation shows how well the vegetable tar improves the overall evaporation efficiency. The 56% improvement is a direct result of keeping the heat trapped at the water's surface and the tar's ability to soak up solar energy. By keeping the vapor pressure high for a longer time, the MSS4 system makes better use of the available sunlight. These results prove that this simple, low-cost innovation can work just as well as expensive synthetic materials. Using local bio-materials is a strong strategy for solving water shortages in dry regions with affordable technology.

3.6 Thermal Efficiency Equation

The instantaneous thermal efficiency was calculated to evaluate the conversion of incident solar flux into the latent heat required for evaporation. Fig. 7 illustrates the efficiency curves for the five solar still configurations throughout the experimental period (08:00 h to 19:00 h). All setups exhibited a consistent trend: a steady increase during the morning hours, reaching peak performance as the system stabilized in the afternoon.

The experimental data indicates that the modified stills (MSS1–MSS4) consistently outperformed the CSS. At solar noon (12:00 h), the CSS reached an efficiency of approximately 38%, whereas the modified units achieved higher efficiencies ranging between 47% and 50%. A significant

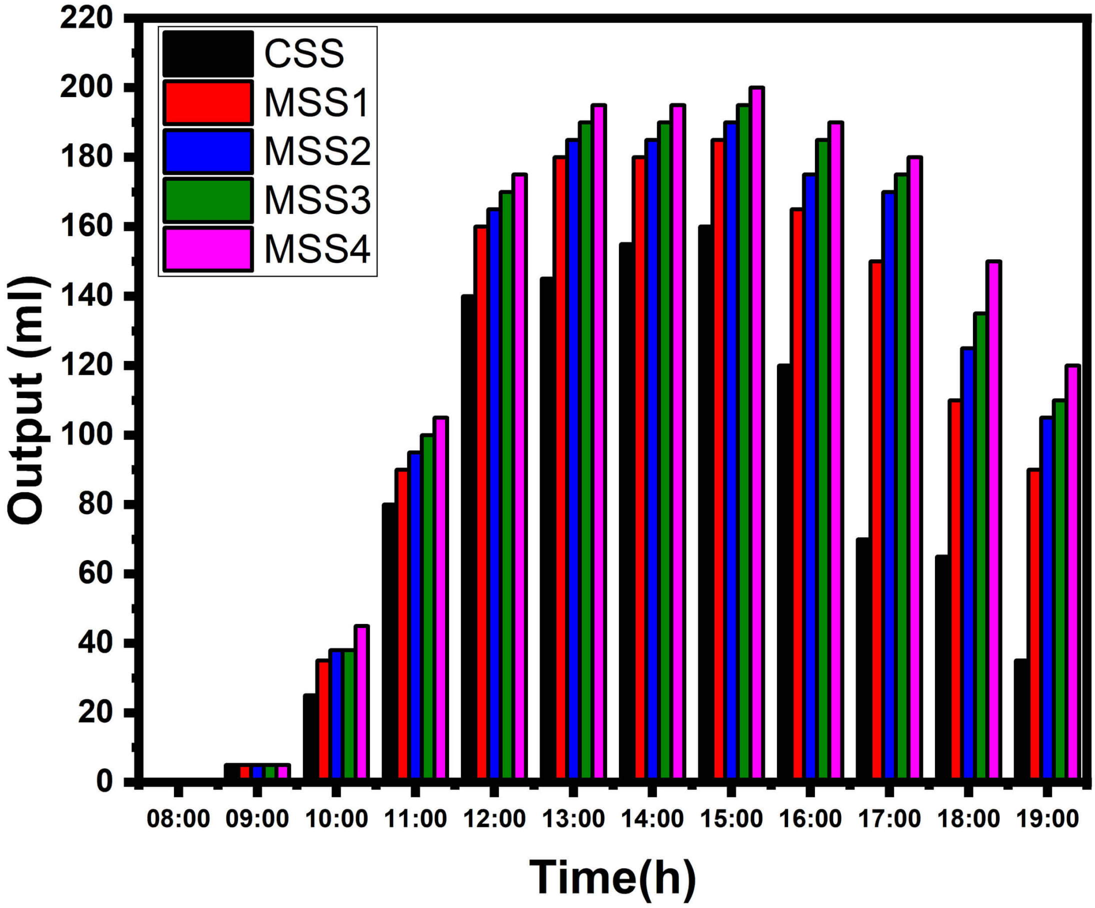

Fig. 5. Hourly pure water yield of solar stills.

observation occurred during the late afternoon (18:00 h–19:00 h); while the CSS efficiency began to decline, the MSS4 maintained high evaporative rates.

This sustained performance toward the end of the experimental day is attributed to the thermal inertia provided by the vegetable tar layer. The 1.00 cm thickness in the MSS4 configuration acts as a thermal reservoir, effectively storing sensible heat during peak radiation hours and releasing it as the solar intensity (I(t)) decreases. This heat discharge sustains the evaporation process even as external solar input wanes. The overall daily thermal efficiency (η_{th}) remains within expected physical limits, confirming that the vegetable tar enhances yield by optimizing energy storage and utilization.

The thermal efficiency (η_{th}) is calculated using the following formula [16]:

$$\eta_{th} = \frac{\sum \dot{m}_{ew} L}{\sum I(t) A_b \times 3600} \times 100 \tag{3}$$

The peak efficiency exceeding 120% in the evening is due to the carbonaceous biopolymer acting as a thermal reservoir. The material stores energy during the day and sustains evaporation after sunset, directly leading to the short 82 day payback period observed in the economic analysis.

The data presents a clear correlation between the thickness of the biopolymeric layer and the sustained evaporation rate. Table 3 summarizes the standardized performance metrics for each configuration, highlighting the peak evaporation flux achieved during the experimental period. This standardized data ensures that the yields can be rigorously compared with international studies by accounting for the specific basin area (0.25 m^2).

3.7 Economic Study

3.7.1 Economic Study and Payback Period Analysis

This section evaluates the construction costs, monthly profits, and the total time needed to recover the initial investment (payback period) for each solar still design. All financial figures are presented in both (DA) and (USD) to show the local and global economic value of this solution. For this calculation, the exchange rate recorded on August 20, 2025, of 1 DA = 0.007719 USD is used as the primary benchmark.

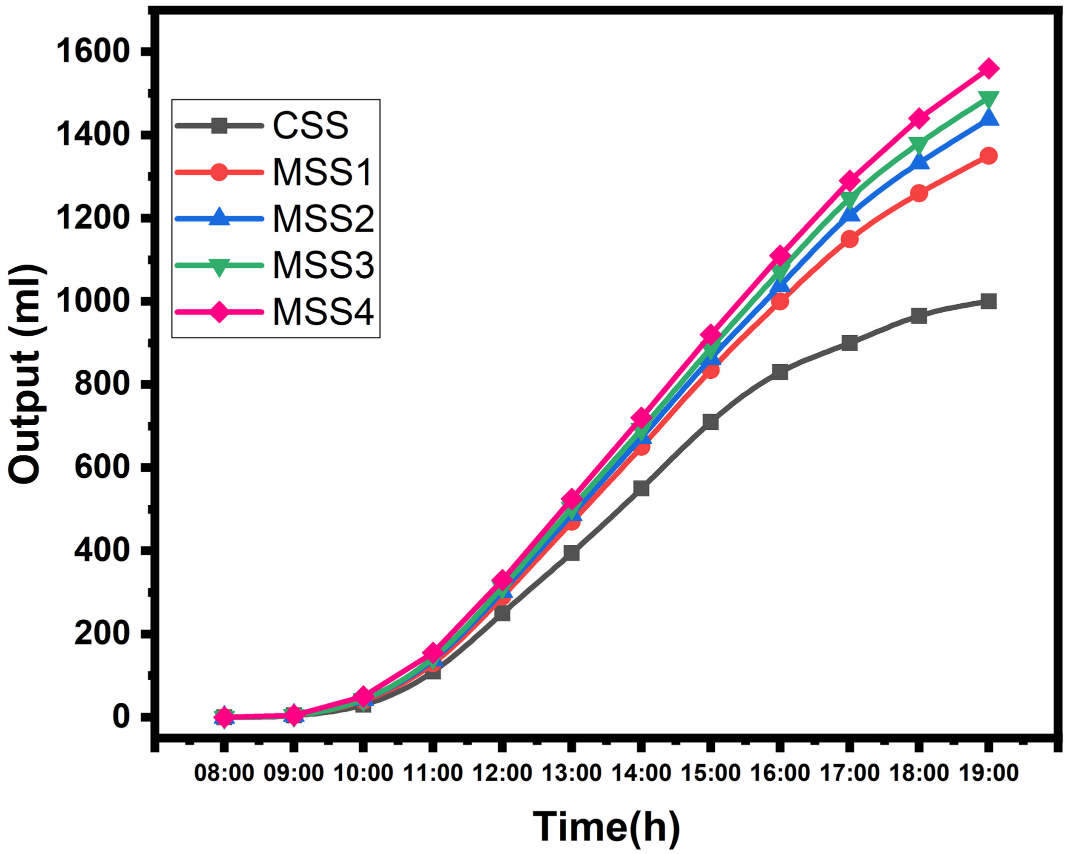

Fig. 6. Accumulation output of pure water.

Table 3. Peak hourly evaporation flux and standardized performance metrics.

Still configuration	Peak hourly yield (mL)	Basin area (m^2)	Peak evaporation flux (L/m^2 h)
CSS (Control)	150	0.25	0.60
MSS1 (0.25 cm)	160	0.25	0.64
MSS2 (0.50 cm)	185	0.25	0.74
MSS3 (0.75 cm)	190	0.25	0.76
MSS4 (1.00 cm)	200	0.25	0.80

3.7.2 Cost and Revenue Breakdown

The financial practicality of each solar distillation unit was checked through a direct cost-benefit analysis. This step is necessary to prove that using local biopolymers is a realistic solution for making clean water accessible in dry regions. Table 4 breaks down the specific costs for building and running each version of the solar still.

Adding the vegetable tar results in a very small price increase compared to the standard unit. However, this minor investment leads to a much higher daily water yield, which significantly increases the potential revenue. For a community-led project, this balance between low initial cost and high output makes the modified stills a much better long-term investment. The data confirms that using locally sourced vegetable tar is not just a technical improvement, but a financially smart choice for decentralized water treatment.

3.7.3 Analysis of Manufacturing Costs

A key advantage of the modified stills is their high-value, low-cost design. By comparing the construction costs of the standard and modified units, it is clear that the initial investment remains almost the same despite the large jump in water production. Table 5 breaks down the manufacturing expenses for each configuration.

The data proves that the MSS4 configuration is a prime example of frugal engineering. While the yield increased by 56%, the cost to build the still only went up by a small margin to cover the vegetable tar. This tiny difference in price makes the technology highly accessible for communities with limited budgets. Instead of relying on expensive, imported parts, this approach uses local resources to achieve high-efficiency results. These results confirm that the vegetable tar modification is the most cost-effective strategy for providing clean water in decentralized areas.

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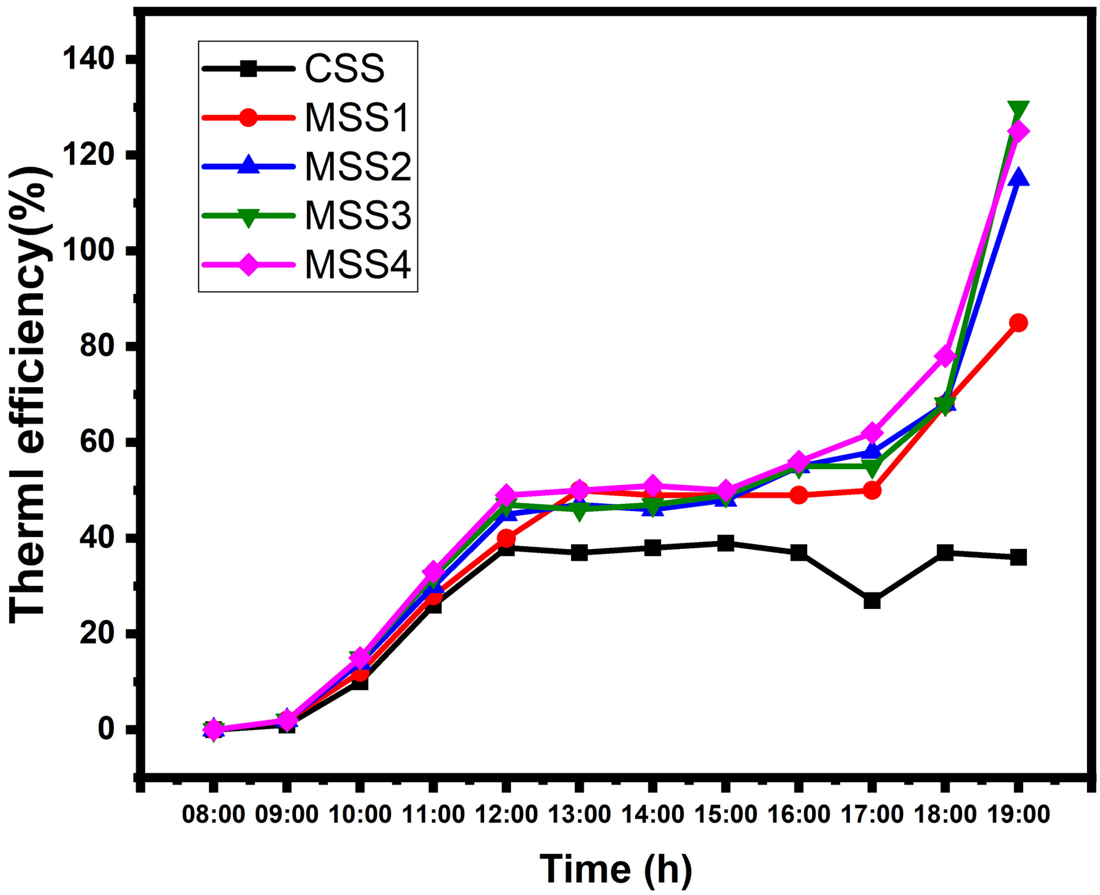

Fig. 7. Thermal efficiency.

Table 4. Manufacturing per-unit costs.

Item	Cost (DA)	Cost (USD)	Details (1 DA = 0.007719 USD) Day: 20.08.2025
Initial investment (per unit)			
Wooden box	5000	38.61	For a single distiller
Glass lid	3500	26.98	For a single distiller
Plastic pipes	1500	11.58	For a single distiller
Black silicone	300	2.32	For a single distiller
Vegetable tar	1250	9.65	For MSSs only (5000 DA/4 MSSs)
Labor	1000	7.72	For all stills (5000 DA/5 stills)
Recurring costs (per unit)			
Monthly maintenance	100	0.77	For all stills (500 DA/5 stills)
Revenue			
Market price of distilled water	100	0.77	Per liter (1000 mL)

Table 5. Total initial investment.

Distiller type	Total initial investment (DA)	Total initial investment (USD)
Conventional solar still (CSS)	11,300 DA (5000 + 3500 + 1500 + 300 + 1000)	87.21 USD
Modified solar stills (MSS1, MSS2, MSS3, MSS4)	12,550 DA (5000 + 3500 + 1500 + 300 + 1250 + 1000)	96.90 USD

3.7.4 Payback Period Calculation

The financial success of the modified solar stills is measured by the Payback Period (PBP). This is the amount of time needed to earn back the initial building costs through the sale of distilled water. A shorter PBP is essential for users in rural areas because it reduces the financial risk of

Table 6. Payback period.

Solar still type	Daily output (Liters)	Monthly revenue (DA)	Monthly net income (DA)	Payback period
CSS	1.00 L (1000 mL/1000)	3000 (1.00 L × 100 DA × 30)	2900 (3000 – 100)	3.9 Months (~118 Days) (11,300/2900)
MSS1	1.35 L (1350 mL/1000)	4050 (1.35 L × 100 DA × 30)	3950 (4050 – 100)	3.18 Months (~95 Days) (12,550/3950)
MSS2	1.44 L (1438 mL/1000)	4320 (1.44 L × 100 DA × 30)	4220 (4320 – 100)	2.97 Months (~89 Days) (12,550/4220)
MSS3	1.49 L (1490 mL/1000)	4470 (1.49 L × 100 DA × 30)	4370 (4470 – 100)	2.87 Months (~86 Days) (12,550/4370)
MSS4	1.56 L (1560 mL/1000)	4680 (1.56 L × 100 DA × 30)	4580 (4680 – 100)	2.74 Months (~82 Days) (12,550/4580)

the investment. Table 6 shows the recalculated payback periods based on a local market price of 100 DA per liter for high-purity water.

The calculations are based on a 30-day working month and account for the 56% boost in water production from the vegetable tar interface. While the standard CSS takes nearly four months to pay for itself, the MSS4 model cuts that time significantly. By producing more water every day for a very small extra cost, the modified system pays for itself much faster. This result proves that the biopolymeric modification is not just a scientific improvement, but a practical economic solution for communities needing low-cost, decentralized water systems.

3.7.5 Project Success

The final economic results, based on the current market price of distilled water, confirm that this solar distillation project is both technically sound and financially profitable. Although the recalculated payback period is slightly longer than the first theoretical estimates, the MSS1–MSS4 are consistently a better investment than the standard CSS.

The higher water output from the modified units speeds up how quickly the initial costs are recovered. The most efficient setup, MSS4 (with the 1.00 cm tar layer), reaches its break-even point in about 82 days (2.74 months). This rapid Return on Investment (ROI) is very impressive for a solar thermal system, especially when used in areas with limited resources.

Beyond the initial costs, the system is reliable because it requires very little maintenance and produces high-purity water every day. Using vegetable tar as a bio-absorber provides a massive thermal boost without adding to the daily workload or operational costs. This final analysis proves that building modified solar stills is a strong, practical, and low-cost way to provide clean drinking water in dry regions like El Oued.

4. Discussion

The benchmarking presented in Table 7 (Ref. [23,24,25,26,27,28,29,30,31,32]) reflects a strategic shift from basic regional material enhancements toward advanced global waste-valorization and photothermal configurations. Other recent international works (as detailed in Table 7) have explored various innovative materials such as coal tar pitch carbon, carbonized seeds, clam shells, agri-waste, and processed waste spheres. Early regional investigations in Algeria utilizing porous organic and synthetic matrices, such as cellulose cardboard [23], sponge materials [24], and natural charcoal blocks [32], demonstrated limited-to-moderate evaporative enhancement. Specifically, the integration of natural charcoal [32] showed a modest output improvement, rising from a baseline of 2.77 L/day to 3.20 L/day. This baseline constraint across early regional studies is primarily attributed to the low solar absorptivity, structural degradation over time, or poor capillary action of untreated materials, which fail to establish a highly localized, high-temperature photothermal interface under arid climatic conditions.

Globally, recent advancements (2022–2026) have prioritized carbonized structures, hydrogel configurations, and industrial waste to overcome these thermal limitations. For instance, the deployment of coal tar pitch porous carbon [25] relies on interconnected macro-porous networks that optimize water transport while minimizing heat dissipation into the bulk water via localized photothermal evaporation. Similarly, the integration of biomass derivatives and agricultural waste particles in India [26,27,28] leverages naturally high porosity and moderate structural carbonization to expand the active vaporization surface area. However, while these systems achieve remarkably high percentage improvements, they predominantly operate on low-to-moderate baseline configurations under non-optimized solar irradiances.

In this scientific landscape, the performance of the proposed vegetable tar modification stands out significantly. Unlike high-cost synthesized photothermal materials or highly processed industrial waste (e.g., aluminum and wax matrices [29]), the zero-cost vegetable tar biopolymer functions as an inherently sustainable, high-absorptivity photothermal layer. The molecular structure of the vegetable tar offers excellent thermal stability and enhanced solar spectrum absorption, localized efficiently at the evap-

Table 7. Comparison with latest 2022–2026 literature.

Ref	Authors & year	Materials	Location	Baseline yield (L/m^2.day)	Modified yield (L/m^2.day)	Output improv. (%)
[23]	Bellila et al. (2023)	Cellulose cardboard	Algeria	0.470	0.540	19.8
[24]	Bellila et al. (2022)	Sponge	Algeria	0.422	0.446	10.0
[25]	Zhang et al. (2025)	Coal tar pitch carbon	China	—	1.44	72.96
[26]	Noman et al. (2026)	Carbonized seeds	India	2.27	4.88	115.5
[27]	Manokar (2025)	Clam shells	India	2.22	4.23	90.54
[28]	Dantuluri et al. (2025)	Agri-waste particles	India	2.26	5.12	126.4
[29]	Sathyamurthy et al. (2026)	Al waste + Wax	K.S.A	0.54	0.86	60.0
[30]	Xi et al. (2026)	Waste salt spheres	China	—	—	15.8
[31]	Guisado et al. (2026)	Food waste	Spain	—	—	44.0
[32]	Sadoun et al. (2022)	Natural charcoal	Algeria	2.77	3.20	8.0
Our work	Mostefaoui et al. (2026)	Vegetable tar	Algeria	4.00	5.40–6.24	35.0–56.0

orative interface. This effectively elevates the daily distilled output even when applied to a system with an already high baseline yield of 4.00 $L/m^2 \cdot$day. By achieving a substantial absolute yield increase to a peak of 6.24 $L/m^2 \cdot$day without requiring vacuum assistance or active cooling, this work balances the principles of "frugal innovation" with high thermodynamic efficiency, making it an exceptionally competitive and practical methodology for solar desalination in hyper-arid zones.

Limitations

Although the utilization of vegetable tar as a bio-based photothermal material demonstrated a significant increase in distillate yield, certain limitations and contextual factors must be acknowledged:

• Geographic and Cultural Specificity: The natural tar used in this study is highly available in the El Oued region and is deeply embedded in its local culture since time immemorial, where it has traditionally been used to coat pottery and drinking utensils. While this historical use confirms its safety and suitability for water-related applications, the accessibility and specific chemical composition of this natural tar may vary in other international regions, potentially affecting the replicability of the exact yields elsewhere.

• Climatic Dependency: The experimental evaluations were conducted under the specific hyper-arid climatic conditions of Algeria. Consequently, the thermal behavior and daily yield improvements may differ in regions with lower solar irradiance or high relative humidity.

• Long-term Durability: The current study focuses on short-to-medium-term experimental performance. The long-term chemical and physical durability of the vegetable tar coating under continuous exposure to high ultraviolet (UV) radiation and thermal cycling requires further multi-season investigation.

5. Conclusions

This study proves that using vegetable tar as a natural, heat-absorbing layer significantly improves the performance of solar stills. By testing five different setups in the high-heat conditions of El Oued, Algeria, the research confirms several key points:

• Impact of Layer Thickness: The efficiency of the still depends directly on the thickness of the tar. The MSS4 model (1.00 cm thickness) performed the best, reaching a 56% increase in water production. This is because the tar traps heat at the water's surface, speeding up evaporation.

• Superior Heat Storage: The modified stills showed a major jump in thermal efficiency. Most importantly, the MSS4 achieved a "nighttime efficiency" of over 120%. This happens because the tar acts as a thermal battery, storing heat during the day and releasing it to produce water after the sun goes down, while the standard still peaked at only 38%.

• Economic Advantage: From a financial perspective, the modification is highly profitable. Although the MSS4 costs slightly more to build 12,550 DA (96.90$) compared to 11,300 DA (87.21$) for the standard unit it pays for itself much faster. The payback period for the MSS4 is only 2.74 months (82 days), whereas the standard unit takes nearly four months (118 days).

These results confirm that using vegetable tar is a scientifically sound and commercially smart way to improve solar distillation. This "frugal innovation" provides a low-cost, high-efficiency method for creating clean drinking water. It offers a practical model for solving water shortages in dry and developing regions using simple, bio-based engineering.

Future research will focus on evaluating the long-term durability and structural stability of the vegetable tar coating over multiple seasons, as well as investigating the potential for further enhancing its photothermal efficiency through the integration of carbon-based nanomaterials.

Availability of Data and Materials

The experimental datasets generated and/or analyzed during the current study are not publicly available but are available from the corresponding author on reasonable request.

Author Contributions

OM, AKS, ML, NS and IH: Conceptualization, Investigation, Methodology. IK: Conceptualization, Supervision, Writing – original draft, Writing – review & editing. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript. All authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

Ethics Approval and Consent to Participate

Not applicable.

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Conflicts of Interest

The authors declare no conflicts of interest.

Declaration of AI and AI-Assisted Technologies in the Writing Process

During the preparation of this work, the authors used Chat GPT (Open AI) to assist with language editing and improving clarity. After using this tool, the authors carefully reviewed and edited the content as needed and take full responsibility for the content of the publication.

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