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Comparative experimental study on the performance of single-slope, hemispherical, and conical solar stills

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Abstract

Although there is a great supply of groundwater, it is salty, and most places of the globe, including the Algerian desert, have a shortage of fresh water. The greatest answer to this issue is solar distillation since it uses sustainable solar energy. Solar still comes in a variety of forms, dimensions and styles, creating potable water that is fresh, clean, and safe to drink, albeit the amount of water produced differs depending on the type of solar still. Choosing the design of solar stills remains one of the preferred solutions to improve their performance. The performance of three different solar still designs is compared in this work, including single slope, hemispherical, and conical solar stills. The investigation used brackish water with a salt level of 3000 ppm and was conducted under the same operational conditions and locations. The conical solar still had the best overall performance, with a daily average production of 5.80 l/m^2/day. The hemispherical solar still had the second-best performance, with a daily average production of 5.10 l/m^2/day. Finally, the single slope solar still had the lowest performance (daily average production of 3.30 l/m^2/day). The findings can be used to develop and improve solar stills for saltwater desalination.

Keywords: Hemispherical; Conical; Single slope; Solar still; Energy and exergy efficiency

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1. Introduction

Water scarcity is a pressing global issue, with a significant portion of the world's population facing challenges in accessing safe and sufficient water resources. As freshwater supplies continue to decline due to factors such as climate change, pollution, and population growth, the need for innovative and sustainable solutions such as water desalination has become increasingly urgent [1]. Desalination, the process of removing salts and impurities from seawater or brackish water to produce potable water, offers a promising pathway to alleviate water scarcity and ensure a reliable supply for domestic, agricultural, and industrial needs. By implementing desalination technologies, communities can enhance water security and reduce the adverse impacts

Nomenclature

A – surface area, m^2/s
$\dot{E}x$ – exergy, kJ
I – solar radiation intensity, W/m^2
$\dot{m}$ – mass flow rate, kg/s
T – temperature, °C

Greek symbols
λ_{fg} – latent heat of vaporisation, J/kg
η – efficiency, %

Subscripts and Superscripts
amb – ambient
dest – destruction
evap – evaporation
fw – fresh water
in – input
out – output
sc – solar collector
sys – system

Abbreviations and Acronyms
FEM – finite element method
CM – composite materials
CoSS – conical solar still
HFU – high-frequency ultrasonic (atomiser)
HFUSS – high-frequency ultrasonic solar still (atomiser)
HSS – hemispherical solar still
NPCMSS – nano-PCM modified solar still
PCM – phase change material
SS – solar still
SSSS – single-slope solar still
TDS – total dissolved solids
TSS – tubular solar still

of water shortages on public health, food production, and economic development. Among the various desalination methods, thermal and membrane-based processes are the most widely used [2,3]. However, conventional desalination techniques often rely heavily on fossil fuels for energy, making them environmentally and economically unsustainable [4,5]. This highlights the need for a renewable energy-powered desalination system [6].

Salt can be extracted from saline water using solar energy through two principal methods: direct and indirect solar desalination [7,8]. In direct systems, solar radiation is absorbed directly by the desalination unit, where it is used to heat the saline water, inducing evaporation and subsequent condensation to produce freshwater. Indirect systems, on the other hand, involve the use of external solar collectors, such as flat plate or evacuated tube collectors that harness solar thermal energy, which is then transferred to the desalination unit. This configuration enables greater control over thermal input and can enhance the overall efficiency and productivity of the desalination process [9]. Solar distillation is a sustainable and effective method for desalinating saline or brackish water, and it has been successfully applied in various regions around the world [10]. Among the different solar desalination technologies, solar stills (SSs) represent one of the oldest and most widely adopted approaches for producing clean water. Their simplicity, low cost, and reliance solely on solar energy make them particularly suitable for decentralised and off-grid applications. In recent years, solar stills have received renewed attention as a viable solution to the global water crisis, especially in arid and semi-arid regions. Numerous experimental studies have been conducted to investigate and improve the efficiency of solar stills. The basin-type solar still, characterised by a shallow water basin and transparent cover, remains the most traditional and commonly used configuration for harnessing solar radiation to produce potable water [11]. Despite their advantages, the practical application of solar stills faces certain challenges. Their performance declines with increasing salinity levels in the feedwater, as higher total dissolved solids (TDS) reduce the evaporation rate. Additionally, their deployment at larger scales is often limited by the extensive surface area required for meaningful output, along with the associated costs of materials, construction, and long-term maintenance. These constraints have driven ongoing research into improving the design and efficiency of solar still systems [12,13].

Dev et al. [14] conducted an annual performance study on an active SS with two independent still evacuated solar tubes. The results demonstrate that during daylight hours, the collector's standalone thermal efficiency is 48% on average. The performance of the integrated collector and solar system is greatly impacted by ambient temperature change, which reduces efficiency by about 5−8%. The use of a high-frequency ultrasonic atomiser (HFU) was investigated to see if it may boost the efficiency of a SS [15]. The daily productivity of SS was 3.58 l/m^2 and that of HFUSS was 4.41 l/m^2, according to the results. Kabeel et al. [16] conducted experiments on SS that had been upgraded using high-efficiency dehumidification of air. The daily output, humidification efficacy, and total efficacy of the improved system were calculated as 18.25 l/m^2, 79% and 39%, respectively. Theoretical and practical evaluations of fixed pyramid and flat plate solar collectors with low costs have been conducted [17]. In order to determine whether a high-frequency ultrasonic atomiser could enhance the efficiency of a solar still, an experiment was carried out by Attia et al. [12].

Improving the design of SSs has been one of the key topics of research. Researchers have examined the influence of several design elements, including the shape and dimensions of the still, on its efficacy. Taamneh et al. [18] determined that a pyramid-shaped solar still was more effective than a flat plate still regarding water production rate and quality. A study conducted by Bellila et al. [19] demonstrated that augmenting the surface area of the still by a multi-layered design enhanced the clean water production rate. Extensive studies have been conducted on pyramid-shaped solar stills, which have demonstrated superior performance compared to traditional flat configurations [20]. The geometrical advantages of the pyramidal design include uniform solar capture throughout the day, reduced side-wall shading, and the elimination of the need for solar tracking mechanisms. Literature analyses further highlight that the performance of a solar still is governed by a range of interrelated factors [21]. These include the depth of water in the basin, the temperature of the glass cover, ambient air velocity, the temperature of the incoming saline water, internal vapour dynamics, and the thermal properties of the materials used for the basin, insulation, and cover [22]. Optimising these parameters is critical to enhancing the overall efficiency and productivity of the system. Consequently, optimising performance necessitates the adjustment of all pertinent parameters.

Furthermore, recent investigations have included comprehensive analyses of the energy, exergy, and economic performance of solar stills [23]. Experimental studies have shown that integrating heat storage materials, particularly a composite of paraffin wax and black gravel, can significantly enhance system efficiency [12,13,24]. These materials improve thermal retention during non-sunlight hours, reduce temperature fluctuations, and sustain evaporation rates, thereby contributing to higher freshwater yield and overall system effectiveness [25,26]. The utilisation of composite material enhanced SS productivity, and energy and exergy efficiencies by approximately 3.27 l/m^2, 48.22% and 3.08%, respectively, yielding improvements of around 37.56%, 38%, and 37% compared to the system employing phase change material (SS-PCM). A novel technique has been implemented to diminish the surface tension and boundary layers in the water of the solar still basin. The novel design utilised water dripping unobstructed through fissures in a solar still tray, presenting a significant benefit. The efficacy of a solar still was examined by altering the number of fissures (7, 10 and 14 fissures) in the suspended surfaces of the trays, facilitating the unobstructed flow of water [27]. A computational and experimental evaluation was conducted by integrating a solar air heater with a multi-compartment solar distiller [28]. Advancing research and development in solar distillation technology could mitigate these limitations, enhancing the accessibility and prevalence of this method [2]. An experiment was conducted to investigate the enhancement of distillation output in a conical solar distiller by utilising inexpensive energy storage materials. This study aims to determine the optimal spacing between stainless-steel balls, each having a fixed diameter of 0.014 m, to enhance the efficiency of conical solar stills by using them as a cost-effective energy storage medium [29].

The present research offers a novel and comprehensive comparative evaluation of three solar still configurations (single-slope, hemispherical and conical) under identical environmental and operational conditions. While numerous studies have explored modifications to individual solar still geometries or examined hybrid systems, direct experimental comparisons of distinct geometric designs within the same testing environment remain scarce in the literature. This study distinguishes itself by not only quantifying and comparing daily water productivity, thermal efficiency, and exergy efficiency of each design, but also by integrating an economic evaluation based on payback period and fabrication cost. Additionally, the study provides new insights into the thermodynamic behaviour of solar stills by analysing exergy destruction mechanisms related to each geometry, thereby contributing to a deeper understanding of the influence of design on performance. By employing brackish water representative of real-world conditions (3000 ppm) and rigorously measuring performance metrics over a full diurnal cycle, this work presents actionable findings that can guide practical design decisions for decentralised desalination systems in arid and semi-arid regions.

2. Materials and methods

To carry out the experimental investigation, three solar still designs were constructed and tested under identical climatic conditions. The fabrication process followed standardised procedures using consistent materials to ensure uniform thermal behaviour across configurations. This section provides a detailed account of the geometric specifications, construction materials and insulation methods used for each still. Additionally, the arrangement of the experimental setup, environmental monitoring tools and measurement protocols are described to ensure clarity and reproducibility of the procedures.

2.1. Experimental setup description

2.1.1. Hemispherical solar still

The hemispherical solar still is designed to optimise solar energy capture and internal heat retention through its symmetrical, dome-shaped geometry. The unit consists of a circular wooden basin with a diameter of 0.36 m, serving as the saline water reservoir. It is covered with a transparent hemispherical dome fabricated from a 0.003 m thick acrylic sheet, measuring 0.4 m in both diameter and height. This geometry maximises the exposure of the inner surface to incident solar radiation from multiple angles throughout the day, enhancing thermal absorption and promoting uniform heat distribution. Figure 1 presents a schematic diagram of the hemispherical solar still, illustrating its structural components and layout. To reduce thermal losses, the basin is insulated along its base and sidewalls using thermally resistant material, thereby improving the overall thermal efficiency of the system. The smooth inner curvature of the acrylic dome also facilitates efficient condensation of vapour, allowing distilled water to flow downward and collect along the perimeter.

2.1.2. Conical solar still

The conical solar still is designed to enhance solar energy concentration and streamline condensate collection through its tapered geometry. The system features a circular wooden basin with a surface area of 0.1 m^2, serving as the brackish water reservoir. A conical transparent acrylic cover, 0.002 m thick, with a base diameter of 0.4 m and a height of 0.12 m, encloses the still from the top. The conical geometry improves the angular reception of solar radiation throughout the day and supports a natural downward flow of condensed droplets toward the collection perimeter. To minimise heat losses, thermal insulation is applied along the base and outer walls of the basin. The reduced internal volume and steeper surface gradient of the conical design allow for higher localised temperatures and more efficient condensation due to the shorter vapour travel distance. These features collectively contribute to enhanced thermal performance and freshwater productivity. A schematic representation of the conical still are presented in Fig. 2.

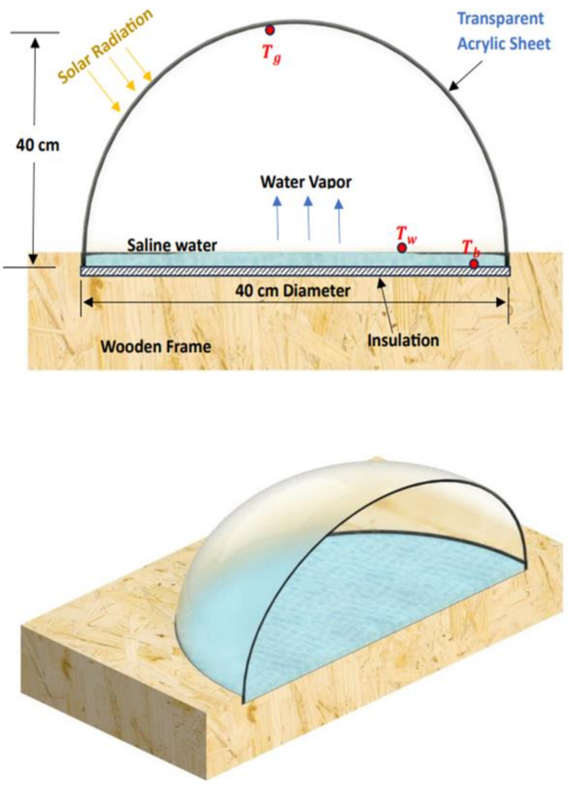


Fig. 1. Schematic representations of the hemispherical solar still design used in the experimental setup, highlighting geometric configuration, materials and insulation layout.

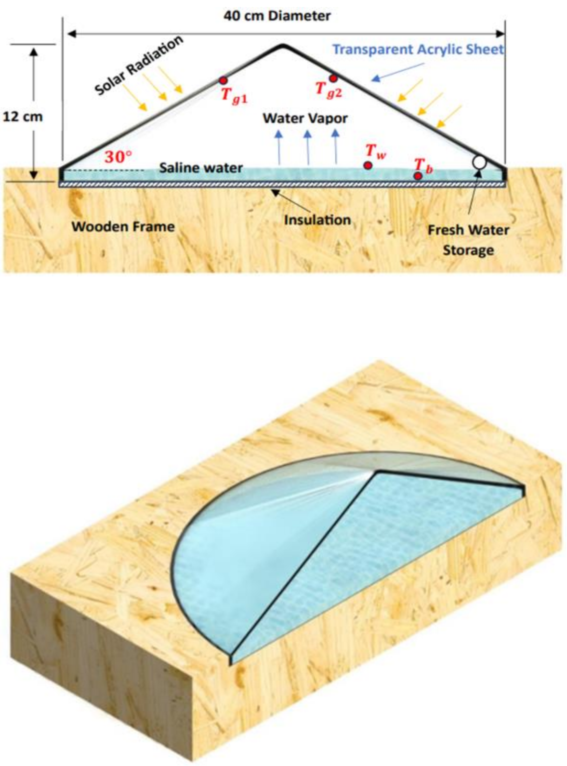


Fig. 2. Schematic representations of the conical solar still design used in the experimental setup, highlighting geometric configuration, materials and insulation layout.

2.1.3. Single-slope solar still

The single-slope solar still represents a conventional design widely used in solar desalination studies. It consists of a rectangular wooden basin with a surface area of 0.25 m^2, used to hold the saline water. The structure features an inclined transparent glass cover (0.003 m thick), supported by a sloped frame, with the front and rear wall heights measuring 0.06 m and 0.14 m, respectively. This inclination facilitates solar radiation entry and directs condensed water downward to the collection channel. The flat-glass cover design, although structurally simple and cost-effective, presents a longer vapour travel path and relatively higher thermal losses compared to curved geometries. Nevertheless, it serves as a reference benchmark for evaluating the performance of more complex still configurations. A schematic view of the single-slope solar still is presented in Fig. 3.

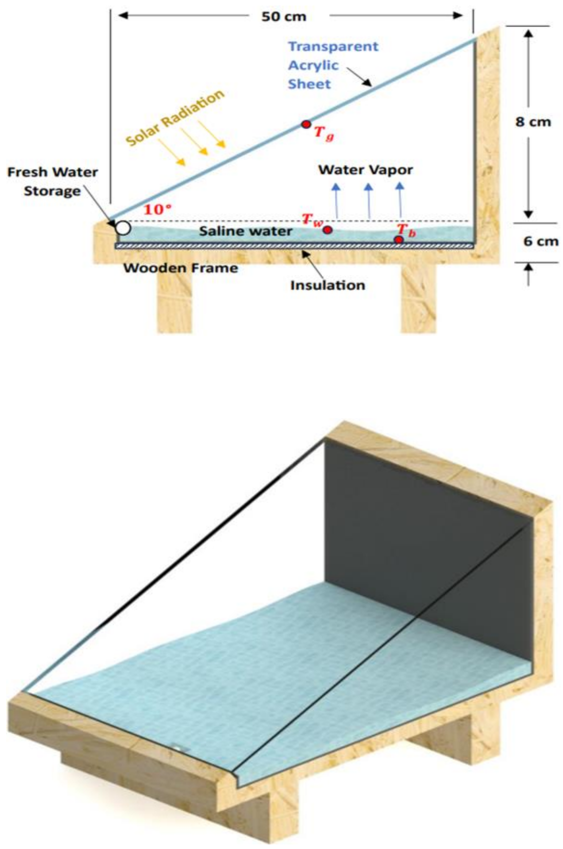


Fig. 3. Pictorial view of the single-slope solar still, illustrating the glass cover angle, basin construction and insulation arrangement.

2.2. Experimental instrumentations

This study investigates and compares the performance of three solar desalination systems: single-slope, hemispherical, and conical solar stills. All three configurations were fabricated using consistent construction materials to ensure a fair comparison. The basins of the stills were constructed from wood and thermally insulated, while the transparent covers varied in geometry and material as per each design. The stills were mounted on a shared wooden support frame to maintain uniform orientation and exposure to solar radiation during the experiments, as illustrated in Fig. 4. It is noteworthy that the three solar still designs investigated in this study

Fig. 4. Photograph of the full experimental setup showing the placement of the three solar still types (single-slope, hemispherical and conical) under identical outdoor environmental conditions.

differ in their basin surface areas. The single-slope solar still features a basin area of 0.25 m^2, whereas both the hemispherical and conical stills have smaller basin areas of approximately 0.10 m^2. To ensure a scientifically valid and equitable comparison across configurations, all performance indicators are rigorously normalised per unit surface area. This normalisation eliminates geometric bias and enables a direct assessment of how design geometry influences system performance under identical environmental conditions. Such an approach enhances the analytical robustness of the study and supports the generalisability of the findings to various scales and applications.

The experimental tests were conducted on June 3, 2023, from 07:00 to 18:00 under outdoor conditions in El Oued city, Algeria. To ensure a fair and controlled comparison, all three solar stills were tested simultaneously on the same day under identical environmental and operational conditions. This approach eliminates variations that could arise from fluctuating weather patterns across different days and ensures that differences in performance are attributable solely to the design characteristics of the stills. A constant water depth of 0.01 m was maintained in the basin of each still throughout the test period to standardise thermal behaviour and evaporation potential across configurations. Although the experiment was conducted over a single day, the side-by-side setup, consistent construction materials, and uniform exposure to solar radiation, temperature, and ambient conditions provide a reliable basis for comparative analysis. This methodology aligns with standard practice in comparative solar distillation studies, where simultaneous testing is prioritised to ensure internal consistency.

To monitor thermal performance, calibrated temperature sensors were installed in each still to record the basin water temperature, inner and outer cover temperatures, and ambient air temperature. Thermocouples were placed at the centre of the basin to ensure an accurate representation of the bulk water temperature. Solar radiation was measured at the basin level using a pyranometer, and the quantity of distilled water produced was recorded hourly using a graduated flask.

Data were collected at 60-minute intervals. Each measurement was subject to known uncertainty, and the instrumentation specifications are as follows:

- Temperature sensors: measurement range of 0–500°C, accuracy ±0.10°C, uncertainty ±0.08°C;
- Solar power meter (pyranometer): measurement range of 0–1999 W/m^2, accuracy ±10.0 W/m^2, uncertainty ±5.78 W/m^2;
- Graduated flask (enumerated beaker): capacity of 0–500 ml, accuracy ±1.000 ml, uncertainty ±0.50 ml.

Environmental conditions during the experimental day were characteristic of the hot, arid climate of El Oued, Algeria, and are crucial for interpreting the system performance. Figure 5 presents the hourly variation of ambient air temperature and solar radiation intensity on June 3, 2023. Solar irradiance peaked near midday at approximately 1000 W/m^2, while ambient temperature reached a maximum of around 40°C. Relative humidity ranged between 18% and 28% during the test period, contributing to favourable evaporation conditions. Wind speed was relatively low, averaging between 1.5 m/s and 2.0 m/s, which helped minimise convective heat loss from the covers while maintaining natural air circulation around the units. Sky conditions remained consistently clear throughout the day, with no observed cloud cover or weather disturbances. These stable and high-radiation conditions ensured that all three solar stills operated under uniform and repeatable environmental conditions, allowing for a valid performance comparison under real-world conditions.

The feedwater used in all three solar stills was brackish water with a salinity level of approximately 3000 ppm, measured in terms of TDS. This salinity level was deliberately selected to reflect typical real-world brackish water conditions, especially in arid and semi-arid regions, where groundwater often falls within this range. According to classifications by the World Health Organisation (WHO) and various water resource management agencies, water with TDS levels between 1000 ppm and 5000 ppm is considered moderately brackish and represents a common challenge for decentralised desalination applications. The use of 3000 ppm ensures that the results are both technically relevant and practically applicable. Furthermore, water salinity directly influences evaporation rates,

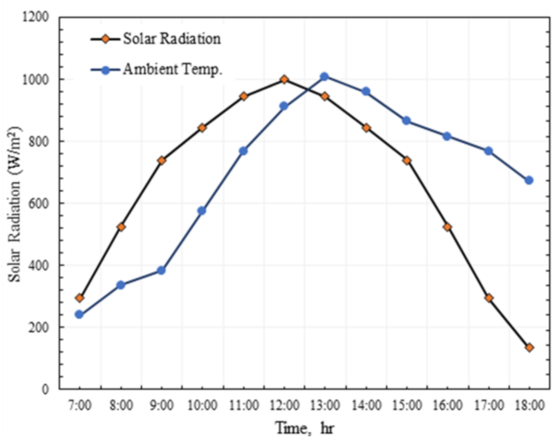


Fig. 5. Hourly variation of ambient air temperature and solar radiation intensity recorded during the experimental day, illustrating typical diurnal environmental conditions in El Oued, Algeria.

as higher salinity reduces the vapour pressure of water, thereby lowering the evaporation potential and thermal efficiency. Conversely, lower salinity increases evaporation due to higher vapour pressure. By selecting a mid-range brackish salinity, the study balances representativeness with system sensitivity, making the findings generalizable to a wide range of real-world desalination scenarios.

3. Performance parameters

3.1. Energy efficiency

Energy efficiency is a fundamental metric for evaluating the thermal performance of solar desalination systems. In the context of solar stills, it is defined as the ratio of the useful thermal energy used to vaporise the feedwater to the total solar energy incident on the collector surface. The useful energy output corresponds to the latent heat required for the phase change of water from liquid to vapour, while the input is the solar radiation absorbed by the basin area. The energy efficiency of the system, denoted as η_{sys}, is calculated as [30]

$$\eta_{sys} = \frac{\dot{m}_{fw}\,\lambda_{fg}}{A_{sc}\,I} \times 100, \tag{1}$$

where $\dot{m}_{fw}$ represents the mass flow rate of freshwater produced, λ_{fg} is the latent heat of vaporisation of water, A_{sc} is the surface area of the solar collector, and I denotes the solar radiation intensity incident on the basin surface. This formulation quantifies how effectively the solar still converts the available solar energy into useful thermal energy for distillation. However, it does not account for losses due to irreversibilities or inefficiencies in heat transfer mechanisms, which are better captured through exergy analysis.

3.2. Exergy efficiency

Exergy efficiency provides a more comprehensive assessment of system performance based on the second law of thermodynamics. Unlike energy, which is conserved, exergy is subject to destruction due to irreversibilities within the system. These irreversibilities arise from entropy generation associated with non-ideal heat transfer, conductive and convective losses, and phase change processes. The exergy balance for a solar still system can be represented by the general form [31]:

$$\sum \dot{E}x_{in} - \sum \dot{E}x_{out} = \sum \dot{E}x_{dest}. \tag{2}$$

For this study, the equation is adapted in the following form:

$$\dot{E}x_{sun} - \left(\dot{E}x_{evap} + \dot{E}x_{work}\right) = \dot{E}x_{dest}, \tag{3}$$

where $\dot{E}x_{sun}$ is the exergy input supplied by solar radiation, $\dot{E}x_{evap}$ is the exergy output associated with water evaporation, $\dot{E}x_{work}$ represents any mechanical or auxiliary work input (considered negligible in passive systems), and $\dot{E}x_{dest}$ denotes the exergy destruction due to irreversibilities. These irreversibilities are influenced by the thermal gradients, heat conduction through materials, and the temperature difference between the basin water and the ambient environment.

As a rough approximation to reversible operation, values for exergy efficiency, i.e. 2nd law efficiency, range from zero to one, corresponding to the worst case (complete exergy destruction) and the best case (no exergy destruction), respectively. As a result, a system's exergy efficiency during a process can be expressed as [32]:

$$\eta_{Ex} = \frac{\text{Exergy recovered}}{\text{Exergy supplied}} = 1 - \frac{\text{Exergy destroyed}}{\text{Exergy supplied}}, \tag{4}$$

$$\eta_{Ex} = \frac{\dot{E}x_{out}}{\dot{E}x_{in}} = 1 - \frac{\dot{E}x_{dest}}{\dot{E}x_{in}}. \tag{5}$$

This formulation reflects the system's ability to convert available solar exergy into useful output while minimising entropy generation. Exergy input from solar radiation is estimated using Petela's model, which accounts for the temperature difference between the sun and the ambient environment [33–35]:

$$\dot{E}x_{in} = \dot{E}x_{sun} = A_{sc}\,I\left[1 - \frac{4}{3}\left(\frac{T_{amb}+273}{T_{sun}}\right) + \frac{1}{3}\left(\frac{T_{amb}+273}{T_{sun}}\right)^4\right], \tag{6}$$

where T_{amb} is the ambient air temperature and T_{sun} is the effective blackbody temperature of the sun, typically assumed to be 5727°C (6000 K). The useful exergy output resulting from the evaporation process is given by the following formula [2,30]:

$$\dot{E}x_{evap} = \dot{m}_{fw}\,\lambda_{fg}\left[1 - \frac{T_{amb}+273}{T_{sun}}\right]. \tag{7}$$

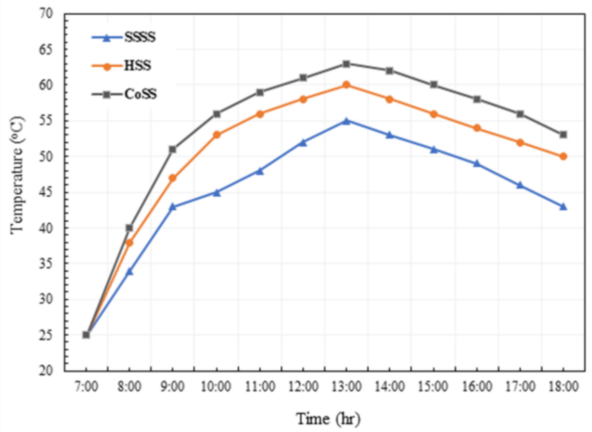
This equation incorporates the temperature difference between the heat source and the environment, emphasising the degradation of energy quality due to irreversible processes. Solar still designs that reduce internal thermal gradients and enhance heat transfer, such as conical and hemispherical geometries, tend to exhibit lower exergy destruction. Consequently, these configurations are more effective in converting incident solar radiation into useful work, as reflected in higher exergy efficiencies. The application of exergy analysis in this study enables a deeper thermodynamic interpretation of performance differences among the tested solar stills, beyond what is possible through energy efficiency alone.

4. Results and discussion

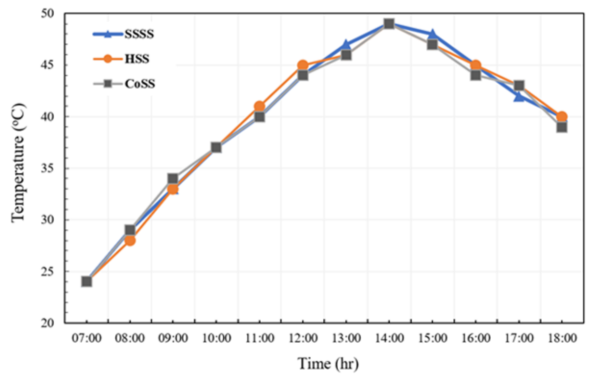
This section presents a comprehensive analysis of the experimental results obtained from the single-slope solar still (SSSS), hemispherical solar still (HSS), and conical solar still (CoSS). Performance metrics include basin water and glass temperatures, freshwater productivity, system (thermal) efficiency and exergy efficiency. The discussion draws upon heat transfer and thermodynamics principles to explain the influence of geometric configuration on solar still performance.

4.1. Thermal behaviour

Figure 6a shows the hourly variation of basin water temperature for all three designs. The CoSS recorded the highest basin temperatures, peaking at around 63°C, followed by the HSS and then the SSSS. This behaviour is primarily attributed to the geometric concentration effect inherent in the conical design,

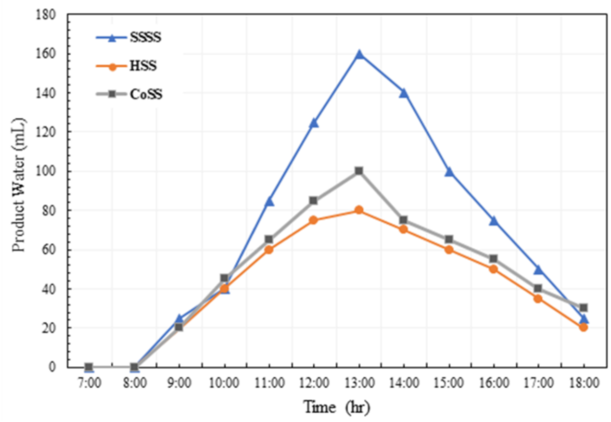


(a) Hourly variation of basin water temperature

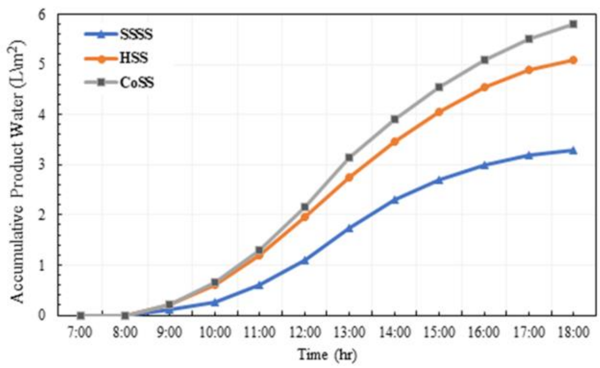


(b) Internal glass cover temperature trends

Fig. 6. Thermal profiles of the solar stills under identical environmental conditions.



(a) Hourly freshwater output from each solar still design



(b) Cumulative distilled water production over the 11-hour test period

Fig. 7. Distillate output profiles of the solar stills.

which facilitates more uniform and multi-angle solar energy absorption throughout the day. CoSS also reduces radiative and convective losses due to its smaller surface-to-volume ratio, a principle supported by Fourier's law of heat conduction, which indicates that heat loss is directly related to surface area and temperature gradient. HSS also achieved relatively high water temperatures due to its dome-shaped acrylic cover, which acts as a natural solar concentrator and enhances internal thermal circulation via buoyancy-driven convection. In contrast, the SSSS exhibited a broader surface area and flat geometry, which increased conductive and convective heat losses, leading to lower water temperatures and reduced thermal gradients.

Figure 6b shows the internal glass cover temperatures. These remained relatively consistent across the three systems due to uniform ambient conditions and solar exposure. However, minor differences suggest that internal air circulation, governed by natural convection patterns and geometry, slightly affects the heat transfer from vapour to the condensation surface. This underscores the role of convective heat transfer coefficients in determining the temperature distribution across system boundaries.

4.2. Freshwater productivity

Figure 7 illustrate hourly and cumulative freshwater yields. CoSS achieved the highest yield at 5.8 l/m^2/day, followed by the HSS at 5.1 l/m^2/day and SSSS at 3.3 l/m^2/day. These results align with fundamental thermodynamic concepts, considering the latent heat of vaporisation, which governs the energy requirement to convert water into vapour. As CoSS reached the highest basin temperatures, it enabled a higher rate of evaporation due to greater thermal energy availability per unit mass of water. Furthermore, the CoSS geometry enhances internal vapour flow and reduces condensation path length, lowering the associated pressure and thermal resistance, key contributors to vapour transfer rate as described by Fick's law of mass diffusion and Newton's law of cooling. HSS, while also effective, exhibits slightly lower performance due to a more moderate thermal gradient and longer vapour paths. SSSS shows the lowest yield due to greater surface heat loss and weaker natural convection within the enclosure.

4.3. Thermal and exergy efficiencies

Figure 8 presents the hourly system (thermal) efficiencies. CoSS attained a maximum efficiency of approximately 70% at midday and maintained an average of 39.3%. HSS and SSSS achieved average efficiencies of 35.3% and 25%, respectively. These outcomes reflect the ability of each design to harness and utilise incident solar radiation for water vaporisation. The superior performance of CoSS can be explained by its compact geometry, which minimises surface heat losses (in line with the Stefan-Boltzmann law of radiative loss) and concentrates energy input

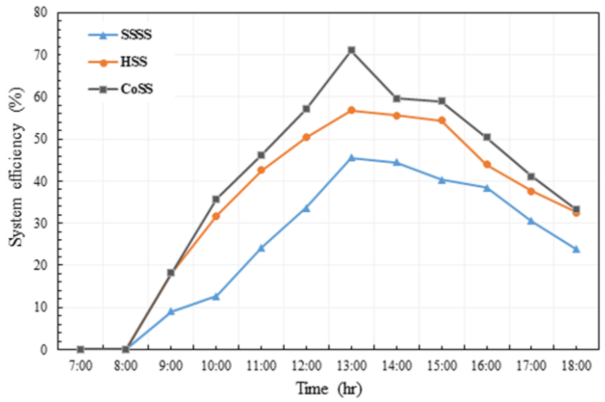


Fig. 8. Hourly thermal (system) efficiency of the solar stills.

on a reduced volume of water, leading to more effective energy conversion.

Figure 9 demonstrates the hourly exergy efficiency, which evaluates the portion of useful work extractable from the system. Exergy destruction occurs due to irreversibilities such as non-isothermal heat transfer, vapour condensation at non-equilibrium conditions and thermal resistance at interfaces. CoSS demonstrated the highest exergy efficiency at 2.9%, followed by HSS (2.1%) and SSSS (1.1%). The higher exergy efficiency of CoSS reflects its ability to minimise entropy generation, consistent with the second law of thermodynamics. This is further supported by Petela's model, which accounts for the degradability of solar energy in terms of the temperature difference between the absorber and the sun.

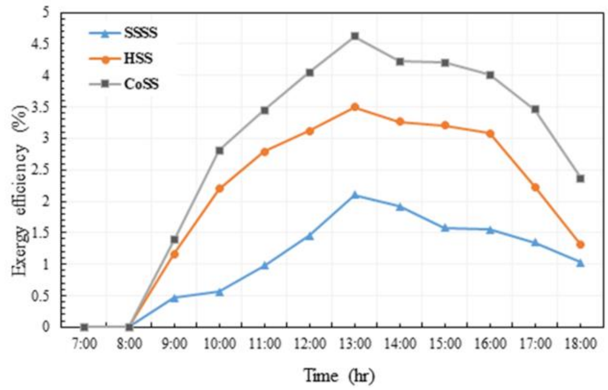


Fig. 9. Hourly exergy efficiency of the solar stills.

4.4. Comparative performance analysis

A comparative summary of the experimental results alongside selected studies from the literature is presented in Table 1. The performance indicators considered include daily freshwater productivity, system (thermal) efficiency, and exergy efficiency. This comparison highlights the effectiveness of the tested geometries, single-slope solar still, hemispherical solar still and conical solar still, in relation to various conventional and modified solar still configurations.

Table 1. Comparison of different SS systems.

System	Productivity (l/m²/day)	System efficiency (%)	Exergy efficiency (%)	Ref.
SSSS	3.300	25.00	1.10	Present study
HSS	5.100	35.30	2.10	Present study
CoSS	5.800	39.30	2.90	Present study
SS	0.690	49.29	9.48	[38]
SS	1.250	30.07	3.67	[37]
SS-PCM	1.485	30.96	3.48	[39]
SS	3.320	34.80	–	[40]
SS-PCM	3.270	48.22	3.08	[36]
SS-CM	2.440	66.87	4.08	[36]
TSS	3.450	51.00	–	[41]
NPCMSS	6.850	–	–	[42]
SS	1.240	35.00	–	[27]

The productivity achieved for the studied systems (5.8 l/m^2/day for CoSS, 5.1 l/m^2/day for HSS and 3.3 l/m^2/day for SSSS) not only validate the superior performance of CoSS under real outdoor conditions but also demonstrate a substantial improvement over several other reported stills, including traditional basin-type designs and even modified systems employing phase change materials (PCM) or composite materials (CM). For example, while SS-PCM reported by Kabeel et al. [36] achieved a productivity of 3.27 l/m^2/day, close to that of SSSS, CoSS exceeded it by nearly 77%, without relying on advanced or costly material enhancements.

From a system efficiency perspective, CoSS reached 39.3%, which, although slightly lower than the highest reported value of 66.87% for SS-CM, is notable considering CoSS used a passive, geometry-based enhancement rather than material or energy input augmentation. HSS also demonstrated strong performance at 35.3%, outperforming several conventional and PCM-based designs. SSSS, while lower in performance (25%), still compares favourably to several earlier configurations with simpler setups [37].

In terms of exergy efficiency, CoSS exhibited a notable performance of 2.9%. This value is within the range of several enhanced configurations reported in the literature, including systems employing phase change materials and composite modifications. For example, SS-PCM and SS-CM systems have demonstrated exergy efficiencies in the range of 3.08% to 4.08%, suggesting that geometric optimisation, as applied in CoSS, can yield comparable thermodynamic benefits without requiring additional thermal storage enhancements or complex integrations. Furthermore, certain advanced designs, such as the nano-PCM modified solar still (NPCMSS) configuration, have reported high levels of productivity, reaching up to 6.85 l/m^2/day. While this underscores the potential of material-based augmentation, the absence of complementary thermal and exergy efficiency metrics presents challenges in conducting a holistic performance comparison. It is also important to consider that system enhancements through geometric redesign, as exemplified by CoSS, may offer practical advantages in terms of construction simplicity and scalability, particularly in resource-constrained settings.

Overall, the comparative results demonstrate that CoSS offers an optimal balance of high productivity, efficiency, and practical design simplicity. It competes strongly with more complex or hybrid systems while maintaining the inherent advantages of passive solar distillation: low cost, easy maintenance and sustainability. These findings reinforce the potential of geometry-based optimisation as a viable and scalable solution for decentralised water production in water-scarce regions.

5. Economic evaluation

An economic evaluation was conducted to assess the cost-effectiveness and financial feasibility of the three solar still configurations. The analysis considered daily freshwater productivity, fabrication and material costs and the payback period for each design.

The experimental data, shown in Table 2, indicate that CoSS achieved the highest daily yield, producing 5800 g/m^2/day, followed by HSS with 5100 g/m^2/day and SSSS with 3300 g/m^2/day. When compared to SSSS, these values correspond to productivity improvements of approximately 75.75% for CoSS and 54.54% for HSS. These results highlight the influence of geometric design on distillation efficiency and the potential for significant gains in water output through relatively simple structural modifications.

The total fabrication costs, which include expenses for construction materials, thermal insulation and black paint coating, were calculated to be 57.78 USD for SSSS, 65.36 USD for HSS and 65.01 USD for CoSS. Based on a market price of 0.60 USD per litre for distilled water, the economic return of each configuration was estimated. CoSS demonstrated the shortest payback period of 18 days, reflecting its higher daily output and reasonable cost. The HSS followed with a payback period of 21 days, while the SSSS required 29 days to recover its initial investment. The detailed cost breakdown of the experimental setup is delineated in Table 3.

Overall, the economic assessment confirms that CoSS offers the most favourable performance-to-cost ratio among the three configurations. While SSSS is more economical to construct, its lower productivity leads to a slower return on investment. In contrast, both CoSS and HSS provide a more balanced trade-off between capital cost and performance.

Table 2. Comparison of the daily productivity obtained from different solar stills.

Parameter	Solar stills		
	SSSS	HSS	CoSS
Daily yield (g/m²)	3300	5100	5800
Improvement rate (%)	–	54.54	75.75

Table 3. Cost of fabrication of solar stills.

Cost breakdown	SSSS	HSS	CoSS
Fabrication cost of the solar still (USD)	43.73	49.20	49.20
Thermo-insulation cost (USD)	10.54	10.54	10.54
Black matt paint (USD)	3.51	3.51	3.51
Total (Investment) (USD)	57.78	65.36	65.01
Productivity (l/m²/day)	3.30	5.10	5.80
The cost per litre of distilled water on the market (USD)	0.60	0.60	0.60
The price of daily water production (USD)	1.98	3.06	3.48
Payback period (day)	29.00	21.00	18.00

6. Conclusion and future recommendations

This study experimentally evaluated the performance of three solar still configurations: single slope (SSSS), hemispherical (HSS) and conical (CoSS), under identical environmental conditions. Based on thermal, exergy, and economic assessments, the following key findings were observed:

- CoSS demonstrated the highest daily freshwater productivity at 5.8 l/m²/day, followed by HSS (5.1 l/m²/day) and SSSS (3.3 l/m²/day).
- The system (thermal) efficiency was the highest for CoSS (39.3%), compared to HSS (35.3%) and SSSS (25%).
- The exergy efficiency, reflecting the ability to minimise thermodynamic irreversibilities, was also the highest for CoSS (2.9%), followed by HSS (2.1%) and SSSS (1.1%).
- The payback period analysis revealed that CoSS had the shortest return period (18 days), making it the most economically favourable design, compared to HSS (21 days) and SSSS (29 days).
- The results confirm that geometry-based design optimisation can significantly enhance both energy and exergy performance without requiring auxiliary power sources or complex material modifications.

These findings highlight the practical and thermodynamic advantages of CoSS and support its suitability for low-cost, decentralised water production in arid and semi-arid regions.

To build upon these findings and advance the practical application of solar stills, the following future directions are recommended:

- Investigating the integration of passive thermal energy storage materials to extend productivity into off-sunlight hours.
- Conducting long-term performance testing under varying seasonal and climatic conditions.
- Future studies should consider metrics like cost per litre and material durability to support long-term viability assessments.

- Exploring automated features for improved maintenance and water collection efficiency.
- Utilising computational optimisation tools to refine design parameters for enhanced performance.
- Performing comprehensive environmental and life-cycle assessments to evaluate scalability and sustainability.

References

[1] Bayoumi, S., Moharram, N.A., Fayed, M., & El-Maghlany, W.M. (2024). Assessing the efficacy of magnetic water treatment: A concise review and experimental investigation. *Desalination and Water Treatment*, 318, 100369. doi: 10.1016/j.dwt.2024.100369

[2] Kabeel, A.E., Diab, M.R., Elazab, M., & El-Said, E.M.S. (2023). Solar powered hybrid desalination system using a novel evaporative humidification tower: A numerical investigation. *Process Safety and Environmental Protection*, 179, 290–313. doi: 10.1016/j.psep.2023.09.015

[3] Moharram, N.A., Konsowa, A.H., Shehata, A.I., & El-Maghlany, W.M. (2024). Advances in zero liquid discharge multigeneration plants: A novel approach for integrated power generation, supercritical desalination, and salt production. *Energy Conversion and Management*, 307, 118352. doi: 10.1016/j.enconman.2024.118352

[4] Moharram, N.A., Bayoumi, S., Hanafy, A.A., & El-Maghlany, W.M. (2021). Techno-economic analysis of a combined concentrated solar power and water desalination plant. *Energy Conversion and Management*, 228, 113629. doi: 10.1016/j.enconman.2020.113629

[5] Moharram, N.A., Bayoumi, S., Hanafy, A.A., & El-Maghlany, W.M. (2021). Hybrid desalination and power generation plant utilizing multi-stage flash and reverse osmosis driven by parabolic trough collectors. *Case Studies in Thermal Engineering*, 23, 100807. doi: 10.1016/j.csite.2020.100807

[6] Moharram, N.A., Konsowa, A.H., Shehata, A.I., & El-Maghlany, W.M. (2025). Sustainable seascapes: An in-depth analysis of multigeneration plants utilizing supercritical zero liquid discharge desalination and a combined cycle power plant. *Alexandria Engineering Journal*, 118, 523–542. doi: 10.1016/j.aej.2025.01.091

[7] Jones, E., Qadir, M., van Vliet, M.T.H., Smakhtin, V., & Kang, S. (2019). The state of desalination and brine production: A global outlook. *Science of the Total Environment*, 657, 1343–1356. doi: 10.1016/j.scitotenv.2018.12.076

[8] Elazab, M.A., Kabeel, A.E., Salem, M., Abueldahab, H., & Elhadidy, S.M. (2023). A review of hybrid humidification and dehumidification desalination systems. *Journal of Engineering Research*, 7(5), 77–88. doi: 10.21608/erjeng.2023.235477.1237

[9] Harris Samuel, D.G., Nagarajan, P.K., Arunkumar, T., Kannan, E., & Sathyamurthy, R. (2016). Enhancing the solar still yield by increasing the surface area of water − A review. *Environmental Progress & Sustainable Energy*, 35(3), 815–822. doi: 10.1002/ep.12280

[10] Suraparaju, S.K., & Natarajan, S.K. (2022). Review on productivity enhancement of passive solar stills. In *Renewable Energy Technologies* (pp. 165–216). Wiley. doi: 10.1002/9781119827634.ch6

[11] Hadi Attia, M.El, Kabeel, A.E., Moharram, N.A., El-Maghlany, W.M.,& Fayed, M. (2025). Enhancing freshwater yield in conical solar stills utilizing external reflective mirrors: An experimental approach. *Solar Energy*, 288, 113287. doi: 10.1016/j.solener.2025.113287

[12] Attia, M.E.H., Kabeel, A.E., Elaloui, E., Abdelgaied, M., & Abdullah, A. (2022). Experimental study on improving the yield of hemispherical distillers using CuO nanoparticles and cooling the glass cover. *Solar Energy Materials and Solar Cells*, 235, 111482. doi: 10.1016/j.solmat.2021.111482

[13] Attia, M.E.H., Kabeel, A.E., Abdelgaied, M., & Abdelaziz, G.B. (2021). A comparative study of hemispherical solar stills with various modifications to obtain modified and inexpensive still models. *Environmental Science and Pollution Research*, 28, 55667–55677. doi: 10.1007/s11356-021-14862-x

[14] Dev, R., & Tiwari, G.N. (2012). Annual performance of evacuated tubular collector integrated solar still. *Desalination and Water Treatment*, 41(1–3), 204–223. doi: 10.1080/19443994.2012.664715

[15] El-Said, E.M.S., & Abdelaziz, G.B. (2020). Experimental investigation and economic assessment of a solar still performance using high-frequency ultrasound waves atomizer. *Journal of Cleaner Production*, 256, 120609. doi: 10.1016/j.jclepro.2020.120609

[16] Kabeel, A.E., El-Said, E.M.S., & Abdulaziz, M. (2019). Computational fluid dynamic as a tool for solar still performance analysis and design development: a review. *Desalination and Water Treatment*, 159, 200–213. doi: 10.5004/dwt.2019.24150

[17] Subramanian, R.S., Kumaresan, G., Ajith, R., Sabarivasan, U., Gowthamaan, K.K., & Anudeep, S. (2021). Performance analysis of modified solar still integrated with flat plate collector. *Materials Today: Proceedings*, 45, Part 2, 1382–1387. doi: 10.1016/j.matpr.2020.06.409

[18] Taamneh, Y., & Taamneh, M.M. (2012). Performance of pyramid-shaped solar still: Experimental study. *Desalination*, 291, 65–68. doi: 10.1016/j.desal.2012.01.026

[19] Bellila, A., Kabeel, A.E., Attia, M.E.H., Dahab, H.A., & Elazab, M.A. (2024). Maximizing solar distillation performance for conical solar still through varied energy storage materials. *Scientific Reports*, 14, 29218. doi: 10.1038/s41598-024-79907-w

[20] Nayi, K.H., & Modi, K.V. (2018). Pyramid solar still: A comprehensive review. *Renewable and Sustainable Energy Reviews*, 81, Part 1, 136–148. doi: 10.1016/j.rser.2017.07.004

[21] Al-Madhhachi, H., & Smaisim, G.F. (2021). Experimental and numerical investigations with environmental impacts of affordable square pyramid solar still. *Solar Energy*, 216, 303–314. doi: 10.1016/j.solener.2020.12.051

[22] Suraparaju, S.K., Samykano, M., Natarajan, S.K., Rajamony, R.K., & Pandey, A.K. (2024). Waste-derived thermal storage solutions for sustainable solar desalination using discarded engine oil and paraffin wax: A techno-environmental feasibility evaluation. *Desalination*, 576, 117318. doi: 10.1016/j.desal.2024.117318

[23] Suraparaju, S.K., Sampathkumar, A., & Natarajan, S.K. (2022). A Mini State of Art Survey on Photovoltaic/Thermal Desalination Systems. In *Advances in Mechanical and Materials Technology (EMSME 2020). Lecture Notes in Mechanical Engineering* (pp. 1–15). Springer, Singapore. doi: 10.1007/978-981-16-2794-1_1

[24] Suraparaju, S.K., Sampathkumar, A., & Natarajan, S.K. (2023). Development of paraffin wax and used cooking oil based composite thermal energy storage for efficient potable water generation in a solar distillation unit. *Journal of Energy Storage*, 69, 107856. doi: 10.1016/j.est.2023.107856

[25] Suraparaju, S.K., Samykano, M., Dhivagar, R., Natarajan, S.K., & Ghazali, M.F. (2024). Synergizing environmental and technological advances: Discarded transmission oil and paraffin wax as a phase change material for energy storage in solar distillation as a step towards sustainability. *Journal of Energy Storage*, 85, 111046. doi: 10.1016/j.est.2024.111046

[26] Suraparaju, S.K., Natarajan, S.K., Mamilla, V.R., Pappala, S.M.T., Kurada, A., & Lakamsani, M.S.V.P. (2023). Energy, exergy, economic and environmental (4E) analyses of solar still with paraffin wax as phase change energy storage material. *Materials Today: Proceedings*, 90, 1–5. doi: 10.1016/j.matpr.2023.03.345

[27] Kabeel, A.E., Diab, M.R., Elazab, M.A., & El-Said, E.M.S. (2024). Multi-sections solar distiller integrated with solar air heater: numerical investigation and experimental validation. *Experimental Heat Transfer*, 37(5), 523–540. doi: 10.1080/

08916152.2022.2164810

[28] Kabeel, A.E., Abdelgaied, M., Attia, M.E.H., Arıcı, M., & Abdel-Aziz, M.M. (2023). Performance enhancement of a conical solar still by optimizing inclination angle. *Solar Energy*, 264, 112001. doi: 10.1016/j.solener.2023.112001

[29] Attia, M.E.H., Kabeel, A.E., & Elazab, M.A. (2023). Performance optimization of a conical solar distillation system with and without stainless-steel balls as low-cost sensible storage: Experimental study and comparative analysis. *Solar Energy*, 266, 112188. doi: 10.1016/j.solener.2023.112188

[30] Attia, M.E.H., Kabeel, A.E., & Elazab, M.A. (2024). Enhancing drinkable water production in conical solar distillers: Comparative analysis of magnet fin heights. *Solar Energy*, 272, 112476. doi: 10.1016/j.solener.2024.112476

[31] Elazab, M.A., Kabeel, A.E., El-Said, E.M.S., Dahab, H.A., Hamed, A.K., Alsaadawi, M.M., & Elbrashy, A. (2024). Exergoeconomic assessment of a multi-section solar distiller coupled with solar air heater: Optimization and economic viability. *Desalination and Water Treatment*, 319, 100535. doi: 10.1016/j.dwt.2024.100535

[32] Dhivagar, R., Suraparaju, S.K., Atamurotov, F., Kannan, K.G., Opakhai, S., & Omara, A.A.M. (2024). Performance analysis of snail shell biomaterials in solar still for clean water production: nature-inspired innovation for sustainability. *Water Science & Technology*, 89(12), 3325–3343. doi: 10.2166/wst.2024.189

[33] González-Mora, E., & Durán-García, M.D. (2024). Assessing parabolic trough collectors and linear Fresnel reflectors direct steam generation solar power plants in Northwest México. *Renewable Energy*, 228, 120375. doi: 10.1016/j.renene.2024.120375

[34] Kabeel, A.E., Diab, M.R., Elazab, M.A., & El-Said, E.M.S. (2022). Hybrid solar powered desalination system based on air humidification dehumidification integrated with novel distiller: Exergoeconomic analysis. *Journal of Cleaner Production*, 379, 134690. doi: 10.1016/j.jclepro.2022.134690

[35] Attia, M.E.H., Kabeel, A.E., Abdelgaied, M., Aljabri, A., & Elazab, M.A. (2024). Performance optimization and comparative study of a conical solar distiller with optimized construction of aluminium balls as energy storage materials. *Desalination and Water Treatment*, 319, 100504. doi: 10.1016/j.dwt.2024.100504

[36] Kabeel, A.E., Abdelaziz, G.B., & El-Said, E.M.S. (2019). Experimental investigation of a solar still with composite material heat storage: Energy, exergy and economic analysis. *Journal of Cleaner Production*, 231, 21–34. doi: 10.1016/j.jclepro.2019.05.200

[37] Sivakumar, V., & Ganapathy Sundaram, E. (2017). Assessment of convective heat transfer coefficient and mass of water evaporated from a single-slope passive solar still by different thermal models: an experimental validation. *International Journal of Ambient Energy*, 38(7), 742–751. doi: 10.1080/01430750.2016.1195777

[38] Methre, V.K., & Eswaramoorthy, M. (2015). Exergy analysis of the solar still integrated nano composite phase change materials. *Applied Solar Energy*, 51(2), 99–106. doi: 10.3103/S0003701X15020115

[39] Shalaby, S.M., El-Bialy, E., & El-Sebaii, A.A. (2016). An experimental investigation of a v-corrugated absorber single-basin solar still using PCM. *Desalination*, 398, 247–255. doi: 10.1016/j.desal.2016.07.042

[40] Rajasekhar, G., & Eswaramoorthy, M. (2015). Performance evaluation on solar still integrated with nano-composite phase change materials. *Applied Solar Energy*, 51(1), 15–21. doi: 10.3103/S0003701X15010119

[41] Essa, F.A., Abdullah, A.S., Omara, Z.M., Kabeel, A. E., & Gamiel, Y. (2021). Experimental study on the performance of trays solar still with cracks and reflectors. *Applied Thermal Engineering*, 188, 116652. doi: 10.1016/j.applthermaleng.2021.116652

[42] Manoj Kumar, P., Sudarvizhi, D., Prakash, K.B., Anupradeepa, A.M., Boomiha Raj, S., Shanmathi, S., Sumithra, K., & Surya, S. (2021). Investigating a single slope solar still with a nano-phase change material. *Materials Today: Proceedings*, 45, 7922–7925. doi: 10.1016/j.matpr.2020.12.804