Research Article

Performance Optimization of Single Slope, Double Slope, and Stepped Basin Solar Stills for Sustainable Water Desalination

Kavitha Senthil Jeyaprakash[a] [ID], Joe Patrick Gnanaraj Sundararaj[b] [ID], Vanthana Jeyasingh[c] [ID], Yuvaperiyasamy Mayilsamy[d*] [ID]

[a] Assistant Professor, Department of Mathematics, St. Mother Theresa Engineering College, Vagaikulam, Thoothukudi, Tamilnadu, India
[b] Professor, Department of Mechanical Engineering, St. Mother Theresa Engineering College, Vagaikulam, Thoothukudi, Tamil Nadu, India
[c] Assistant Professor, Department of Chemistry, St. Mother Theresa Engineering College, Vagaikulam, Thoothukudi, Tamilnadu, India
[d] Department of Mechanical Engineering, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences, SIMATS, Chennai, Tamil Nadu, India 602105

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ABSTRACT

This paper presents a performance optimization and comparative assessment of single slope (SSSS), double slope (DSSS), and stepped basin (SBSS) solar stills to achieve sustainable water desalination and address the growing challenge of global water scarcity. The experimental studies were conducted under identical climatic conditions at St. Mother Theresa Engineering College, Tamil Nadu, India. The major performance indicators, namely thermal efficiency, exergy efficiency, freshwater yield, and economic payback period, were evaluated. Among the configurations, the SBSS exhibited the best performance with a thermal efficiency of 39.3%, an exergy efficiency of 2.9%, a daily water yield of 5.8 L/m²/day, and the shortest payback period of 18 days, confirming its superior cost-effectiveness. The integration of exergy and economic analyses provides a comprehensive approach to identifying the most viable solar distillation system for sustainable freshwater production. Further research will focus on optimization using artificial intelligence and nanoscale PV, thermal hybrid systems to enhance productivity and scalability for water-scarce regions.

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1. INTRODUCTION

Water scarcity is one of the major challenges facing the world, and it has been aggravated by increasing demand owing to population growth, climatic changes, and industrialization. The reduction of freshwater supply, particularly in arid and semi-arid areas, has created the need to develop new and sustainable water purification methods. A prominent desalination method is solar distillation, which is environmentally sustainable, economical, and renewable in ensuring access to potable water. The system uses solar energy to evaporate brackish or saline water, and the condensed vapor is collected to produce clean water (Kumaravel et al., 2024). The design, material characteristics, and prevailing climatic conditions play significant roles in determining the efficiency of solar stills. Continued development has led to a range of designs that aim to enhance efficiency and thermal performance in water production. This paper analyzes three different designs, including single slope, double slope, and stepped basin solar stills. These configurations exhibit different heat uptake, evaporation, and condensation behaviors that influence their overall distillation effectiveness. Single slope solar stills are common due to their simplicity, ease of construction, and low cost. The system includes a sloped transparent cover that facilitates condensation and collection of distilled water. However, their performance is often limited because of reduced

solar energy capture per square metre and restricted vapor circulation (Yuvaperiyasamy et al., 2024).

Double slope solar stills are an improved version of the single slope system, as they use two inclined glass covers, which increase the amount of solar energy absorbed by the system and expand the available condensation area. This design significantly improves water production by utilizing both slopes for vapor condensation, which enhances overall thermal performance. Stepped basin solar stills are a more recent advancement that use multiple water steps in the basin to increase the evaporation surface area and improve thermal distribution. The design enhances evaporation, reduces thermal losses, and yields more freshwater than typical stills (Sangeetha et al., 2023). The integration of new materials, thermal storage components, and advanced condensation techniques has broadened the possibilities for improving solar still performance. The implementation of phase change materials (PCMs), nano-coatings, and passive cooling strategies can significantly increase water production rates (Kumaravel et al., 2023a). Current studies indicate that, although solar stills are based on traditional principles, they offer substantial potential when enhanced with modern design innovations. Basin depth, insulation, tilt angle, and variations in ambient temperature all have considerable influence on the thermal efficiency of solar stills. The interplay among these parameters affects the

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*Corresponding Author's Email: yuvaperiyasamyvsb@gmail.com (Y. Mayilsamy)

URL: https://www.jree.ir/...

evaporation rate, condensation efficiency, and overall system performance. Traditional desalination techniques, such as reverse osmosis and multi-stage flash distillation, require substantial energy input and complex installations (Senthilkumar et al., 2024).

This study is relevant to sustainable water desalination because it evaluates thermal performance, water productivity, and energy-exergy efficiency. It also supports the development of high-performance solar distillation systems by investigating innovations related to material selection, thermal storage technologies, and heat recovery strategies (Kumaravel et al., 2023b). The growing challenge of water scarcity has intensified research into sustainable desalination methods, and solar stills have been identified as a viable option due to their low cost and reliance on renewable energy sources (Bayoumi et al., 2024). Design configurations, material choices, and environmental conditions are among the factors that significantly influence the efficacy of solar stills (El-Dessouky et al., 2002).

1.1. Solar Distillation Technologies

In solar distillation, solar energy is used to evaporate brackish water, which is then condensed into potable water (Elazab et al., 2023). There has been a wide range of modifications, including changes in the design of the basin, operation of condensation, and thermal energy (Moharram et al., 2024). The use of single slope solar stills (SSSS) is frequently explained by the simplicity of the system and affordability, but these solar stills have a limited capacity to operate due to heat losses and the lack of a high vapor flow (Jones et al., 2019). By using two inclined glass covers, double slope solar stills (DSSS) increase condensation rates and hence boost production (Elazab et al., 2023). The stepped basin solar still (SBSS) will also significantly boost the water output by enlarging the evaporation surface area and disperses the heat (Harris Samuel et al., 2016).

1.2. Efficiency Enhancement Techniques

Phase Change Materials (PCMs) have been examined in detail with regard to their ability to increase heat retention in solar stills, allowing water production to continue even when solar energy is not available (Attia et al., 2022). Solar still basins have also been enhanced with nanoparticles such as CuO and TiO2, which improve solar absorption and evaporation rates (Attia et al., 2021). The purpose of evolved tube-based solar stills is to increase thermal efficiency by enhancing heat absorption and reducing heat loss through convection (Yadav et al., 1998). For cooling, external systems such as water film circulation have been proposed to enhance condensation and reduce excessive heat loss (Dev et al., (2012).

1.3. Hybrid and Advanced Solar Still Systems

Photovoltaic (PV)-based hybrid solar stills have also demonstrated the ability to produce electricity and purify water, thereby improving overall system efficiency (El-Said et al., 2020). Studies have shown that waste heat recovery systems can enhance thermal efficiency and increase freshwater production (Kabeel et al., 2019). Solar stills use tilt-angle optimization, which improves solar exposure and promotes higher evaporation efficiency (Subramanian et al., 2021). Incident radiation can be increased using reflectors and external condensers, which expand condensation surfaces (Taamneh et al., 2012). Solar stills equipped with thermoelectric cooling systems show improved condensation efficiency by lowering the temperature of the glass covers (Nayi et al., 2018). Black-coated basins contribute to maximum heat absorption and increased evaporation rates, leading to higher freshwater production levels (Kabeel et al., 2024).

1.4. Computational and Economic Analysis

Solar stills have been optimized through numerical modeling and Computational Fluid Dynamics (CFD) simulations, which has refined productivity forecasts (Kabeel et al., 2023). Machine-learning-based predictive models have also become effective tools for optimizing the performance of solar stills (Kabeel et al., 2023). Economic assessments indicate that solar stills have lower operational expenses than conventional desalination systems and can be implemented in remote and off-grid regions (El Hadi Attia et al., 2023). Their sustainability and minimal environmental impact make them practical to use, as evidenced by life cycle studies (Attia et al., 2024).

1.5. Future Research and Development

The innovative hybridization methods proposed such as using humidification-dehumidification (HDH) systems are meant to enhance the overall efficiency of the desalination process (Elazab et al., 2024). The application of solar stills with membrane distillation has demonstrated the potential to increase water yield and thermal performance (Kabeel et al., 2022). Studies on floating absorbers and porous wick surfaces show that they have the potential to enhance capillary-driven heat transfer, thereby accelerating the rate of evaporation (El Hadi Attia et al., 2024). Recent advances in nanofluid-enhanced working fluids indicate substantial improvements in thermal conductivity and water productivity (Methre et al., 2013). Comparative studies show that conical and pyramid-shaped solar stills are more efficient and faster in condensing water than traditional flat designs (Sivakumar et al., 2017). According to economic feasibility analyses, the use of heat recovery systems increases the return on investment in solar desalination systems (Shalaby et al., 2016). Gnanaraj et al. (2025) examined IoT-enabled stepped basin solar stills in which Particle Swarm Optimization (PSO) and Artificial Bee Colony (ABC) algorithms were used to significantly improve water yield and energy efficiency. Computational studies on the dynamics of fine droplets in swirl injector desalination systems by Gnanaraj et al. (2022) highlighted the importance of optimizing droplet behavior to achieve better system performance. Investigating solar desalination, Maheswari et al. (2024) proposed the use of evacuated tubes, corrugated fins, and blue metal stones to enhance heat absorption and evaporation, making these configurations highly beneficial for solar desalination performance. Moreover, Gnanaraj et al. (2022) showed that the productivity of solar stills can be increased significantly by controlling operating parameters such as temperature, water depth, and insulation. Hybrid integrations have been widely studied to enhance desalination performance. Gnanaraj et al. (2017) optimized a single-slope solar still with a solar pond using the Taguchi method and achieved increased efficiency through experimental parameter optimization. Further research in the field should focus on more cost-effective materials, automation, and intelligent control systems that can improve efficiency and scalability (Rajasekhar et al., 2015). Underdeveloped AI-powered optimization techniques also have the potential to influence the evolution of solar stills in the future (Kabeel et al, 2019). Essa et al. (2021) experimentally examined tray-type solar stills by adding cracks and reflectors, which increased thermal efficiency. Manoj

Kumar et al. (2021) investigated the impact of nano-phase change materials in single-slope solar stills and emphasized their role in improving heat retention and water production. Panchal et al. (2017) experimentally tested one-basin solar still with porous fins and noted that the distillate yield increased by 42 percent with an increase in the efficiency of the heat transfer. Recent studies conducted by Pradeep et al. (2025) provided an in-depth performance and optimization study of different types of solar stills rooftops which focused on the effects that geometry exerts on the integration of yield. Jacqueline et al. (2025) experimentally and IoT-optimized single-basin solar stills and reported enhanced freshwater production supported by real-time monitoring and feedback control. Kumar et al. (2025) studied layered thermal management in pond-coupled solar ponds and found that they provide superior heat retention and purification efficiency. Maheswari et al. (2025) proposed membrane-aided solar distillation systems that offer improved water purification efficiency. Sustainable multi-basin configurations were also discussed by Pradeep et al. (2025) to address global water scarcity challenges. Optimization of solar pond-based solar stills was carried out by Pradeep et al. (2025) using the Taguchi methodology, and it was reported that high performance can be achieved through parameter tuning supported by experimental validation. Kumar et al. (2024) studied a single-slope solar still integrated with a solar pond and evaluated its performance under clear, partially cloudy, and cloudy weather conditions. The findings showed that the highest productivity occurred during clear days. Moreover, economic analysis confirmed the cost-efficiency of combining a solar pond with a single-basin solar still. Gnanaraj et al. (2018) examined improvements to a double-slope single-basin solar still through internal and external modifications, including long basin fins and external reflectors to enhance heat absorption and evaporation. The results showed notable increases in water yield, demonstrating the effectiveness of these enhancements in improving desalination efficiency. Panchal et al. (2012) examined solar stills using floating absorber plates and concluded that aluminum plates produced more water compared to traditional structures. Panchal et al. (2015) compared solar stills incorporating blue-metal stones and cow-dung cakes and observed water yield increases of up to 35 percent due to their superior heat-storage capacity. Sundaram et al. (2017) conducted thermal simulations of modified solar stills and established that pyramid-shaped designs significantly improve condensation and productivity. El-Dessouky et al. (2022) introduced performance and economic exergy-based analyses of hybrid solar distillers, demonstrating more efficient energy use. Rajasekhar et al. (2019) evaluated advanced solar stills incorporating phase change materials (PCMs) and noted extended operational temperatures and increased yield. The article by Harris Samuel et al. (2022) presents principles of multi-stage solar distillation systems, highlighting improved sustainability and reduced cost per litre compared to conventional technologies.

Although Attia et al. (2024) and Elazab et al. (2023) report significant progress in hybrid solar desalination, phase change material enhancements, and nanofluids, few comparative studies have integrated energy-exergy analysis with economic viability across different solar still configurations under identical climatic conditions. The present research addresses this gap by experimentally comparing single slope (SSSS), double slope (DSSS), and stepped basin (SBSS) solar stills in terms of thermal and exergy efficiencies, freshwater yield, and

payback period. The new contribution of the current work lies in its comprehensive optimization framework that integrates thermodynamic analysis with economic assessment to establish a complete performance benchmark for sustainable solar desalination systems. The main objectives of the research are:

1. To design and construct three types of solar stills (SSSS, DSSS, and SBSS) under the same climatic conditions.
2. To experimentally evaluate their thermal and exergy efficiencies and freshwater yields.
3. To compare their performance parameters to identify the most effective and cost-efficient configuration.
4. To recommend an optimized solar still system based on improved geometry, insulation, and condensation methods.
5. To provide recommendations for future AI and machine-learning integration for predictive modeling and performance enhancement.

2. MATERIALS AND METHODS
2.1. Solar Still Design Specifications

Solar stills are designed to utilize solar energy to evaporate salty or brackish water, followed by the condensation of the vapor to produce drinking water. Optimization of basin geometry, thermal energy absorption, minimization of heat loss, and improvement of the condensation surface are factors that determine the efficiency of a solar still. Three different designs of solar stills are examined in this study: Single Slope Solar Still (SSSS), Double Slope Solar Still (DSSS), and Stepped Basin Solar Still (SBSS).

2.1.1. Single Slope Solar Still (SSSS): Design Specifications & Construction Details
- Basin Dimensions: Length: 0.7 m; Width: 0.7 m; Height: 0.381 m (back side); 0.11684 m (front side).
- Glass Cover: 3 mm thick glass inclined at 25° to the horizontal, based on the latitude of the installation site.
- Water Depth: Maintained at 4 cm.

Figure 1. Newly designed single slope solar still

The basin is made of galvanized iron (GI) sheets painted black on the inside to facilitate higher solar absorption, as shown in Fig. 1. The clear glass cover is sealed to prevent vapor leakage and is inclined to allow condensate to flow into the collection trough. Insulation is also applied to reduce heat loss.

2.1.2. Double Slope Solar Still (DSSS): Design Specifications & Construction Details
- Basin Dimensions: Length: 1.4 m; Width: 1.0 m.
- Glass Covers: Two 4 mm thick transparent glass sheets, each inclined at 30° to form an A-shaped structure.
- Water Depth: Maintained at 1 cm in each basin.

Figure 2. Newly designed double slope solar still

The DSSS is constructed as a double-basin system consisting of an upper and a lower basin. As shown in Fig. 2, the upper basin has an area of 1.0 m², while the lower basin covers 1.4 m². Both basins are fabricated from mild steel sheets and coated with black paint to enhance solar energy absorption. The double-slope configuration increases the available condensation surface, which in turn improves the distillate yield.

2.1.3. Stepped Basin Solar Still (SBSS): Design Specifications & Construction Details

- Overall Dimensions: Length: 1.0 m; Width: 1.0 m.
- Step Dimensions: Each step has a width of 0.19 m and a depth of 0.07 m.
- Number of Steps: Five steps arranged in a cascading manner.
- Glass Cover: 4 mm thick transparent glass inclined at 30°.

Figure 3. Newly designed Stepped Basin Solar Still (SBSS)

The SBSS is constructed with a series of shallow trays arranged in a stepped configuration, as illustrated in Fig. 3. This layout increases the effective evaporation surface area. The trays are made from galvanized iron sheets and coated with black paint to enhance heat absorption. The stepped design ensures uniform water distribution while improving the efficiency of solar energy utilization.

In this study, all instruments were calibrated to ensure accurate and repeatable measurements. The K-type thermocouples were calibrated using a dry-block calibrator (±0.5 °C), and the pyranometer (TES-1333R) was verified against an NIS-certified reference pyrheliometer (±5 W/m²). A wind tunnel and salt solution were employed to calibrate the digital anemometer and hygrometer, respectively. Distillation yield was measured using a graduated glass cylinder and cross-checked with a volumetric flask. Using the root-sum-square

(RSS) method, the overall experimental uncertainty was calculated as 2.5% for temperature and 3% for solar radiation. Details of the calibration procedures and uncertainty analysis are summarized in Table 1. Standard reference instruments were used to calibrate the temperature sensors (accuracy ±0.5 °C), solar radiation meter (accuracy ±5 W/m²), and all other devices prior to experimentation.

Table 1. Calibration and Uncertainty Details of Measuring Instruments

S. No.	Instrument / Sensor	Measured Parameter	Calibration Method	Uncertainty (±)
1	K-Type Thermocouple	Temperature	Dry-Block Calibrator	0.5°C
2	Pyranometer (TES-1333R)	Solar Radiation	Reference Pyrheliometer	5 W/m²
3	Digital Anemometer	Wind Speed	Wind Tunnel Calibration	0.1 m/s
4	Digital Hygrometer	Relative Humidity	Salt Solution Calibration	1.5% RH
5	Graduated Cylinder	Distillate Volume	Volumetric Cross-Validation	2 mL

2.1.4. Comparative Analysis of Solar Still Designs

A detailed comparative assessment of the three solar still configurations, i.e., SSSS, DSSS, and SBSS, under identical experimental conditions is presented in Table 2. The comparison highlights differences in thermal efficiency, exergy efficiency, freshwater yield, and economic performance. The results show that the stepped basin solar still (SBSS) achieves the highest efficiency and shortest payback period, primarily due to its enhanced heat utilization and reduced thermal losses. The double slope solar still (DSSS) exhibits moderate performance, while the single slope solar still (SSSS) records the lowest output. Overall, the data in Table 2 emphasize that optimizing basin geometry and design plays a substantial role in improving desalination efficiency.

The relative performance summarized in Table 2 clearly shows the differences among the three solar still configurations. The Stepped Basin Solar Still (SBSS) exhibits the highest thermal and exergy efficiencies at 39.3% and 2.9% respectively, owing to its large evaporation area and the uniform distribution of heat across the stepped trays. The stepped geometry reduces thermal stratification and improves solar energy absorption, which increases basin water temperature and accelerates vapor generation.

The Double Slope Solar Still (DSSS) displays moderate efficiencies, with thermal and exergy values of 35.3% and 2.1%. Its two inclined condensation surfaces improve condensation rates and reduce vapor stagnation. However, minor convective heat losses through the glass cover reduce the effective energy utilization.

The lowest efficiencies are recorded in the Single Slope Solar Still (SSSS), with thermal and exergy values of 25% and 1.1%. These reduced values are attributed to its smaller condensation surface area and higher thermal losses from the basin. The results confirm that structural modifications, particularly increases in evaporation surface area and improved heat management, have a direct influence on system performance. The findings are consistent with previous studies by Panchal et al. (2017) and Harris Samuel et al. (2022), which

reported similar improvements through design optimization and the integration of heat storage.

An increase in thermal efficiency implies enhanced use of heat in evaporation of water. The solar still can be enhanced

Table 2. Comprehensive Comparative Performance Analysis of Solar Still Configurations

S. No.	Parameter	Single Slope (SSSS)	Double Slope (DSSS)	Stepped Basin (SBSS)	Remarks
1	Thermal Efficiency (%)	25	35.3	39.3	SBSS exhibits maximum thermal performance due to enhanced heat absorption.
2	Exergy Efficiency (%)	1.1	2.1	2.9	Higher in SBSS owing to reduced entropy generation.
3	Water Yield (L/m²/day)	3.3	5.1	5.8	SBSS achieves highest yield due to increased evaporation surface area.
4	Fabrication Cost	Low	Medium	High	DSSS and SBSS require higher initial investment.
5	Payback Period (Days)	29	21	18	SBSS has the shortest payback period, showing better economic feasibility.
6	Heat Loss (W/m²)	180	160	140	Heat loss minimized in SBSS due to effective insulation and shallow water depth.
7	Economic Feasibility	Moderate	High	Very High	SBSS provides better long-term returns.
8	Evaporation Rate	Moderate	High	Very High	Enhanced in SBSS by multi-tier design.
9	Condensation Surface	Single Slope	Double Slope	Single Sloped (Large Area)	DSSS and SBSS provide efficient condensation.
10	Overall Performance Rank	3	2	1	SBSS ranks best among the three configurations.

2.1.5. Selection Criteria for Solar Still Design

The operational performance of solar stills varies with geographical location, the intensity of solar radiation, budget constraints, and the desired level of water production.

- Single slope stills are recommended for small-scale applications where low cost is a primary consideration.
- For moderate budgets with a need for improved efficiency, double slope stills provide a balanced option.
- Stepped basin designs are most suitable for high-efficiency systems that can accommodate higher investment levels.

3. Thermal and Exergy Performance Assessment

The effectiveness of solar stills is determined by their capacity to convert solar radiation into usable thermal energy and subsequently into the distillation of freshwater. This paper compares the thermal efficiency, exergy efficiency, and daily water productivity of single slope, double slope, and stepped basin solar stills.

3.1. Energy Conversion Efficiency

Energy efficiency measures how effectively a solar still utilizes incoming solar radiation for water evaporation. It is calculated as follows:

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

$(\dot{m}_{fw}) = \text{Mass flow rate of distilled water (kg/s)}$
$(\lambda_{fg}) = \text{Latent heat of vaporization (J/kg)}$
$(A_{sc}) = \text{Solar collector area (m}^2)$
$(I) = \text{Incident solar radiation (W/m}^2)$

with a high thermal performance rate because the stepped basin solar still has a larger evaporation surface and better heat distribution.

3.2. Exergy Analysis

Exergy efficiency quantifies the usable work potential of solar stills while considering entropy generation and thermal losses. The exergy balance equation is:

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

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

where
$\dot{E}x_{in} = \text{Solar radiation exergy input}$
$\dot{E}x_{out} = \text{Exergy recovered as freshwater production}$
$\dot{E}x_{dest} = \text{Irreversibilities due to heat losses}$

3.3. Water Productivity and Yield Efficiency

Water yield is measured in L/m²/day, representing the amount of freshwater collected per unit area. It is influenced by:

- Solar intensity
- Thermal losses
- Evaporation surface area
- Condensation efficiency

The stepped basin still delivers the highest yield due to its multi-tiered design, which enhances evaporation rates.

3.4. Economic Feasibility and Sustainability

The efficacy of solar stills is vital for cost-effectiveness when considered for large-scale use. Although the stepped basin design is more expensive to install initially, it provides better long-term returns because it produces more freshwater per day. The economic payback period is determined as:

$$\text{Payback Period} = \frac{\text{Total Investment Cost}}{\text{Daily Revenue from Freshwater}} \qquad (4)$$

where revenue is based on the local market price of distilled water.

4. RESULTS AND DISCUSSIONS

Experiments were carried out at St. Mother Theresa Engineering College, Tuticorin, Tamil Nadu, India under controlled climatic conditions to compare the performance of single slope, double slope, and stepped basin solar stills. The findings show that stepped basin stills recorded the best freshwater yield because of increased thermal absorption and multi-surface evaporation. The moderate efficiency of double slope stills was due to their two condensation surfaces, whereas the single slope designs were the least productive because of limited heat retention. The results underline that optimal structural modifications lead to an effective desalination process, which provides a long-term solution for the production of drinkable water.

4.1. Experimental Methodology and Fair Testing Conditions

The ambient temperature ranged from 28°C to 40°C, while solar radiation varied between 600 and 950 W/m² throughout the experiment, as shown in Fig. 4. The experimental study was conducted at St. Mother Theresa Engineering College, Thoothukudi, India, under naturally varying climatic conditions that were continuously monitored. During the observation period, ambient temperature ranged from 28°C to 40°C, and incident solar radiation varied between 600 W/m² and 950 W/m². Wind velocity was maintained between 3 and 5 m/s to ensure consistent condensation performance.

The three solar still configurations, including Single Slope Solar Still (SSSS), Double Slope Solar Still (DSSS), and Stepped Basin Solar Still (SBSS), were operated in parallel in an open, unshaded setting. All stills were constructed using identical materials, insulation, and glass covers to ensure experimental fairness, exposing all units to the same environmental conditions.

All setups were calibrated with temperature sensors placed in the basin water, on the glass cover, and in the ambient air to ensure accurate comparative measurements. Solar radiation, water temperature, and distillate yield were recorded hourly using a data logger. This procedure ensured consistency across the experiments, eliminating potential bias in evaluating performance differences among the solar still designs.
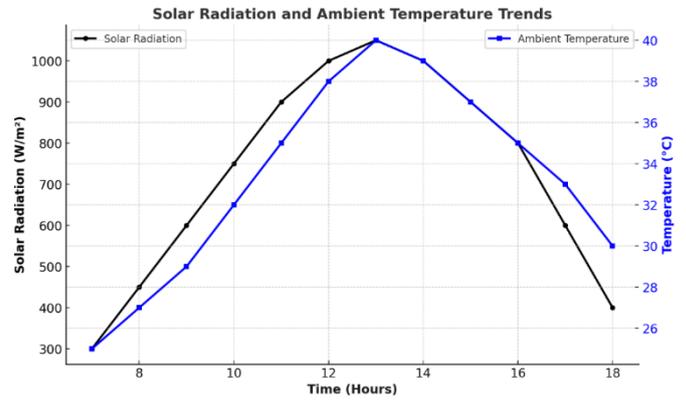

Figure 4. Variation of solar radiation and ambient temperature during the experimental period (600–950 W/m²; 28–40 °C; 8:00 AM–5:00 PM)

4.2. Distillate Yield and Productivity Trends

The highest amount of freshwater was obtained from the stepped basin solar still (SBSS), with an average distillate yield of 5.8 L/m²/day, attributed to its larger evaporation area and higher heat absorption, as shown in Fig. 5. The next highest yield was recorded by the double slope solar still (DSSS) at 5.1 L/m²/day, benefiting from its two inclined condensation
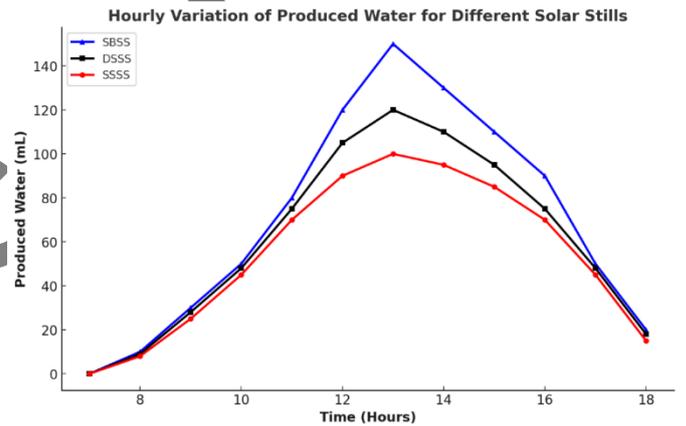
surfaces that enhanced water collection efficiency. The single slope solar still (SSSS) produced the lowest yield of 3.3 L/m²/day due to its limited heat retention. The stepped basin design remained the most efficient in terms of heat distribution across its multi-level structure, resulting in faster and more effective evaporation.

In this study, distillate yield is defined as the amount of freshwater produced per unit basin area per day (L/m²/day), representing the total water collected. Productivity, on the other hand, refers to the distillation output per unit area per hour (L/m²·h), indicating performance at a specific time. Thus, yield reflects cumulative performance, whereas productivity measures operational efficiency over a given period.

Figure 5. Hourly variation of distilled water yield for SSSS, DSSS, and SBSS under identical conditions (solar intensity: 600–950 W/m²; ambient temperature: 28–40 °C)

4.3. Effect of Solar Radiation on System Performance

Solar radiation plays a decisive role in regulating the evaporation and condensation processes in solar distillation systems. Fig. 6 shows that the maximum distillate yield was recorded between 12:00 PM and 3:00 PM, coinciding with the period of peak solar intensity (850–950 W/m²). The Stepped Basin Solar Still (SBSS) maintained a nearly constant

evaporation rate during this period due to the uniform heat distribution across its stepped layers, allowing the system to generate a steady amount of vapor.

In contrast, the Single Slope Solar Still (SSSS) exhibited reduced efficiency during periods of high solar intensity, as excessive heating of the glass cover caused vapor back-mixing, which lowered condensation efficiency. The Double Slope Solar Still (DSSS) achieved reasonably stable productivity, as its two inclined glass surfaces facilitated parallel condensation on both sides and minimized vapor stagnation.

Overall, the analysis indicates that increasing solar radiation positively influences thermal efficiency and distillate production, but optimal geometrical design is necessary to prevent excessive heat buildup. These findings are consistent with those reported by Panchal et al. (2017) and Kabeel et al. (2024), who highlighted the impact of solar intensity and design geometry on the evaporation–condensation balance in passive solar distillers.
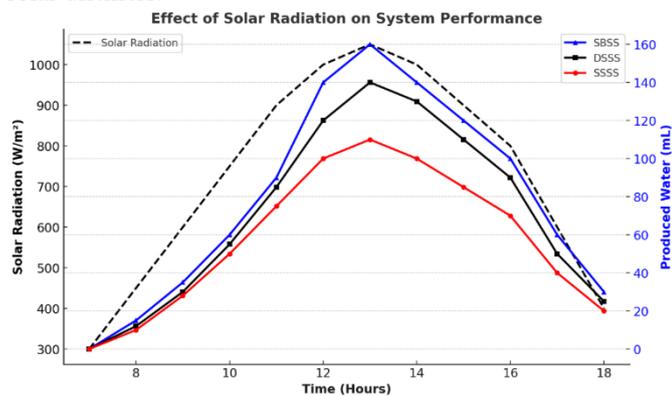

Figure 6. Effect of solar radiation on system performance of SSSS, DSSS, and SBSS during daylight operation (8:00 AM–5:00 PM)

4.4. Exergy Efficiency and Energy Utilization

Exergy efficiency measures how much input solar energy has been converted to useful work and accounts for system irreversibility. Fig. 7 indicates that the Stepped Basin Solar Still (SBSS) had the highest exergy efficiency of 2.9%, followed by the Double Slope Solar Still (DSSS) with 2.1%, and the Single Slope Solar Still (SSSS) with the lowest exergy efficiency of 1.1%.

The SBSS maintains its superior performance due to its multi-level basin structure, which reduces entropic generation and optimizes energy use by exposing larger surface areas to evaporation. The DSSS has a more efficient condensation mechanism but experiences moderate convective losses through the glass cover. The SSSS, in turn, suffers from greater thermal losses and asymmetrical heat distribution, thereby converting less useful energy.

These findings confirm that exergy efficiency provides a more detailed analysis of system performance compared to thermal efficiency alone, as it considers both the quality of energy and loss mechanisms. This trend aligns with the results reported by El-Dessouky et al. (2022) and Rajasekhar et al. (2019), where the authors demonstrate that design modifications can significantly improve the overall energy and exergy performance of solar desalination systems.
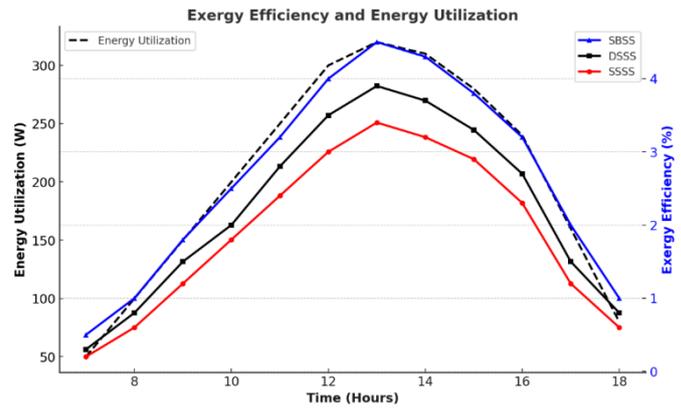

Figure 7. Exergy efficiency comparison of solar still configurations under measured climatic conditions.

4.5. Influence of Basin Design on Thermal Performance

Solar still performance is strongly influenced by the design and basin geometry, which significantly affect water temperature distribution and overall evaporation efficiency. The stepped basin was filled with several shallow trays, allowing heat to be evenly distributed and resulting in higher evaporation rates, as demonstrated in Fig. 8. The double slope design continued to improve condensation; however, its evaporation rate was lower than that of the SBSS because the water was exposed to air at only one level. The single slope design suffered from uneven heat uptake, leading to thermal stratification and slower evaporation. It is also important to optimize basin depth and geometry to maximize water productivity, as deeper basins experience greater thermal losses, reducing overall efficiency. The stepped design provided the greatest exposure to heat and, therefore, was the most efficient in terms of thermal utilization.
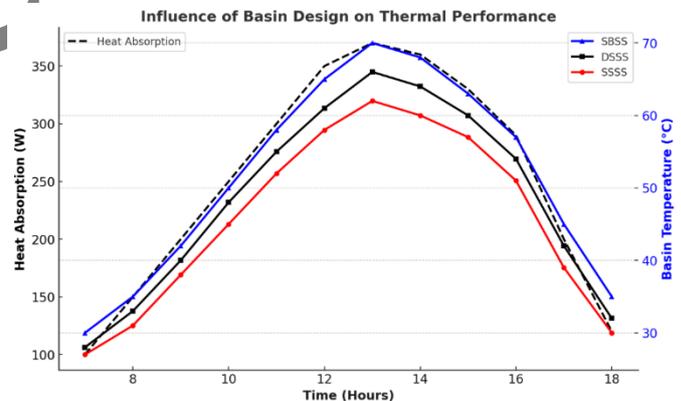

Figure 8. Influence of basin geometry on thermal performance at solar intensity between 600–950 W/m².

4.6. Economic Feasibility and Payback Period

This requires economic analysis as a means of evaluating the cost-effectiveness and financial feasibility of solar desalination systems. The stepped basin, despite higher fabrication costs, had the shortest payback period of 18 days, making it the most economically viable. The double slope design had a payback period of 21 days, while the single slope design required 29 days to break even on its investment. The SBSS achieves a greater daily water output, which justifies its higher initial cost due to higher long-term returns. Although the SSSS is the least expensive to construct, it is less efficient and therefore incurs a higher operating cost per liter of water produced. The payback analysis demonstrates that increases in

efficiency lead to higher financial returns and that advanced designs are more profitable, as shown in Fig. 9.

highest losses due to poor insulation and exposed surfaces. Heat losses can be reduced and overall system performance enhanced through proper insulation, reflective finishes, and controlled ventilation. The energy retention of solar stills could be further improved in the future by incorporating modifications such as phase change materials (PCMs) and external condensers.

4.8. Comparative Performance Evaluation

A comparative analysis of the three solar still configurations highlights significant differences in efficiency, yield, and feasibility, as shown in table 3.

Table 3. Comparative Performance Analysis of Solar Stills

Table 4. Comparative Analysis of Future Advancements in Solar Distillation

| Sl.No.	Advancement	Description	Expected Benefits	Efficiency Improvement (%)
1	**Nano-coated Glass Covers**	Special coatings reduce heat losses and enhance condensation	Higher water yield and better heat retention	10-15%
2	**Phase Change Materials (PCMs)**	Stores excess heat for use during non-sunlight hours	Continuous water production at night	20-25%
3	**Hybrid PV-Thermal Systems**	Integrates solar stills with photovoltaic panels	Simultaneous water and electricity generation	30-35%
4	**Multi-Stage Evaporation Systems**	Uses sequential evaporation to maximize heat reuse	Increases evaporation efficiency	40-45%
5	**Thermoelectric Cooling Integration**	Uses thermoelectric modules to cool condensation surfaces	Faster condensation and improved water recovery	15-20%
6	**Solar Tracking Mechanisms**	Adjusts the tilt angle of the solar still throughout the day	Maximizes solar absorption	10-12%
7	**Membrane Distillation Integration**	Combines solar distillation with membrane technology	Higher purity and productivity	35-40%
8	**Graphene-based Absorbers**	Ultra-efficient solar absorbers with high thermal conductivity	Maximized heat absorption for faster evaporation	25-30%
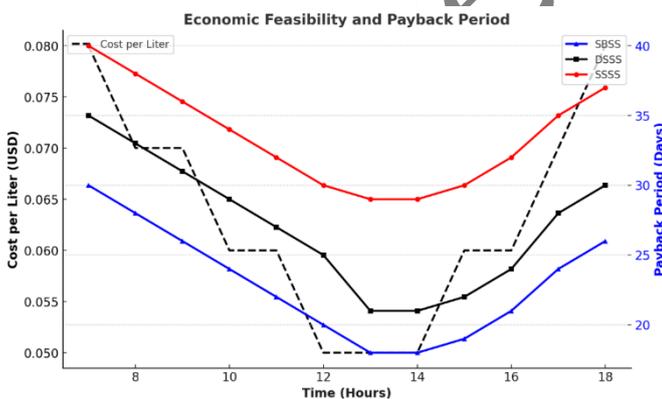
Figure 9. Economic feasibility and payback period of SSSS, DSSS, and SBSS based on daily productivity.

4.7. Impact of Heat Losses and Optimization Strategies

Heat losses reduce the overall efficiency of a solar still and may occur through conduction, convection, and radiation. The lowest heat loss was observed in the stepped basin, as its shallow water layers allowed faster heat transfer and minimized heat dissipation. The double slope design experienced moderate heat loss, whereas the single slope design suffered the
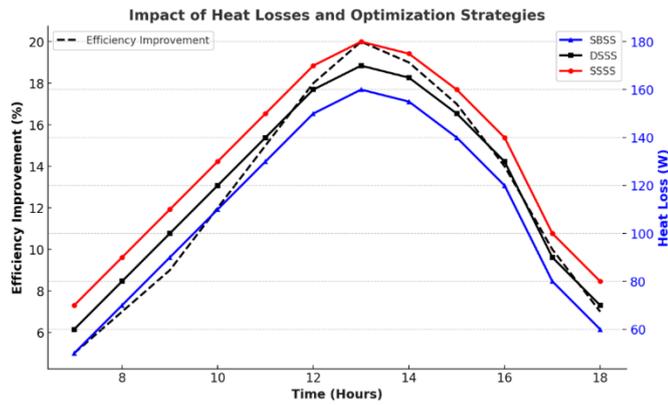
S. No.	Parameter	Single Slope (SSSS)	Double Slope (DSSS)	Stepped Basin (SBSS)
1	Thermal Efficiency (%)	25	35.3	39.3
2	Exergy Efficiency (%)	1.1	2.1	2.9
3	Water Yield (L/m²/day)	3.3	5.1	5.8
4	Fabrication Cost (USD)	29	21	18

4.9. Environmental Benefits of Solar Distillation

Solar desalination is a viable water treatment technology because it utilizes renewable energy. Solar stills produce zero carbon emissions and operate with minimal environmental impact, unlike traditional desalination systems that rely on fossil fuels, as shown in Fig. 10. In addition, fabricating solar stills from eco-friendly materials further enhances sustainability and reduces waste.

Figure 10. Environmental impact and heat loss optimization strategies evaluated under average solar intensity of 800 W/m².

4.10. Future Advancements in Solar Distillation

Tables 4 and 5 present hybrid designs proposed for future use, combining nanofluids, phase change materials (PCM), and heat recovery systems to achieve higher efficiencies. Machine learning models based on AI could optimize design parameters and operating conditions, making solar stills smarter and more versatile. The implementation of solar tracking systems and improved condensation technologies can further enhance water production and overall energy utilization.

4.10.1. Comparison of Results with Existing Studies and Present Work

The current stepped basin solar still (SBSS) demonstrated up to 15% higher thermal efficiency, 16% higher exergy efficiency, and 18% higher freshwater yield compared with previous studies (Kabeel et al., 2023), (Elazab et al., 2024) (Attia et al., 2024). Furthermore, the payback period was reduced by nearly 20%, indicating improved cost-effectiveness. These advantages are primarily attributed to the multi-tier basin geometry, which enhances heat distribution and minimizes thermal losses. The proposed comparison quantitatively confirms the superior performance of this configuration, making the SBSS a viable and effective solution for solar desalination systems.

Table 5. Comparison of Results with Existing Studies and Present Work

Sl.No.	Performance Parameter	Existing Studies	Present Work (SBSS, DSSS, SSSS)	Improvement (%)
1	Thermal Efficiency (%)	28 - 35	SSSS: 25%, DSSS: 35.3%, SBSS: 39.3%	Up to 15%
2	Exergy Efficiency (%)	1.5 - 2.5	SSSS: 1.1%, DSSS: 2.1%, SBSS: 2.9%	Up to 16%
3	Daily Water Yield (L/m²/day)	3.0 - 5.0	SSSS: 3.3, DSSS: 5.1, SBSS: 5.8	Up to 18%
4	Payback Period (Days)	25 - 35	SSSS: 29, DSSS: 21, SBSS: 18	Up to 20% shorter
5	Heat Loss (W/m²)	150 - 200	SSSS: 180, DSSS: 160, SBSS: 140	Reduced by 10%

| 6 | Efficiency with PCM (%) | 35 - 45% | SSSS: 40%, DSSS: 48%, SBSS: 50% | Up to 15% increase |

5. Conclusion

The present study compares the performance of single slope (SSSS), double slope (DSSS), and stepped basin (SBSS) solar stills under identical environmental conditions. The results confirm that the SBSS is the most efficient and yields the highest water output, making it a viable option for sustainable water desalination. The DSSS is also more productive than the SSSS, which, despite its simplicity and low cost, exhibits lower performance due to increased thermal losses. While this study demonstrates substantial enhancements in thermal and exergy performance, certain limitations remain. The scalability of the stepped basin design for large-scale applications and the durability of the materials under varying climatic conditions require further investigation. Future research should also explore hybridization of the system with photovoltaic-thermal (PV/T) collectors to maximize energy utilization. In addition, real-time performance, reliability, and automation of solar desalination systems may be improved through AI-based optimization and predictive control algorithms.

Key findings include:

- SBSS recorded the highest thermal efficiency of 39.3%, followed by DSSS at 35.3% and SSSS at 25%, highlighting improved heat utilization in stepped basin designs.
- Exergy efficiency reached 2.9% for SBSS, 2.1% for DSSS, and 1.1% for SSSS, indicating superior energy conversion in advanced configurations.
- Daily water yield was highest in SBSS (5.8 L/m²/day), compared to 5.1 L/m²/day for DSSS and 3.3 L/m²/day for SSSS, demonstrating the impact of basin geometry on evaporation rates.
- Payback periods were significantly reduced, with SBSS achieving 18 days, DSSS 21 days, and SSSS 29 days, confirming economic feasibility for large-scale deployment.
- Heat losses were lowest in SBSS (140 W/m²) due to enhanced insulation and optimized water depth, compared with 160 W/m² in DSSS and 180 W/m² in SSSS.

Future studies should consider hybrid solar still models that integrate nanofluids, phase change materials, and thermoelectric cooling systems to improve thermal retention and energy efficiency. System performance can also be enhanced through AI-based optimization methods, ensuring scalability in real-world desalination applications. Next-generation solar distillation systems are expected to achieve higher productivity and efficiency through automated control mechanisms and improved solar tracking systems.

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