Performance Enhancement of Single and Double-Slope Solar Stills by Integrating Energy Storage Material: Energetic and Exergetic Approach

UDC:628.165:502.21:523.9
Original scientific paper https://doi.org/10.46793/aeletters.2026.11.3.4

Pavan Kumar Pathak[1], Bholu Kumar[2*], Rahul Agrawal[3]

[1]Research Scholar, Department of Mechanical Engineering, Poornima University Jaipur, Rajasthan, India
[2]Department of Mechanical Engineering, Poornima University Jaipur, Rajasthan, India
[3]Department of Thermal Energy Storage, Iberian Centre for Research in Energy Storage, Cáceres 10003, Spain

Abstract:
Access to safe freshwater remains a challenge, particularly in arid and water-scarce areas. Growing freshwater scarcity due to rapid climate change, industrialization, and population growth has increased the demand for sustainable and decentralized desalination technologies. Solar radiation distillation offers a simple, low-cost, and environmentally friendly solution, but its low productivity limits large-scale adoption. This experimental study investigates performance improvements in a single-slope and double-slope solar still incorporating a eutectic phase change material (EPCM) at a fixed basin water depth of 10 mm under winter (December) and summer (May) conditions. A eutectic mixture of stearic acid with palmitic acid at a melting temperature around 55 °C was used as latent heat storage to stabilize basin temperature and extend distillation during off-sunshine hours. The study analyzed four configurations: a conventional single slope solar still (CSSS), a single slope solar still with eutectic phase change material (SSEPCM), a conventional double slope solar still (CDSSS), and a double slope solar still with eutectic phase change material (DSSSEPCM. December freshwater yields were 1575, 2350, 2000, and 2785 ml, respectively, and increased in May to 1835, 2605, 2355 and 3130 ml. Phase change material (PCM) integration improved night distillation with yields of 580-750 ml in December and 610-810 ml in May for SSSEPCM and DSSSEPCM, which resulted in longer operational periods. The highest energy efficiency was 42.65% in December and 49.3% in May, and the highest exergy efficiency for DSSSEPCM was 17.1% and 18.6%. The proposed Eutectic phase change material-integrated solar stills provide a sustainable and decentralised solution for freshwater production in arid and water-scarce regions, where abundant solar energy is often accompanied by freshwater scarcity.

ARTICLE HISTORY
Received: 13 March 2026
Revised: 19 July 2026
Accepted: 25 August 2026
Published: 23 September 2026

KEYWORDS
Solar desalination, Double slope solar still, Eutectic mixture, Exergy efficiency, Energy efficiency, Freshwater productivity

1. INTRODUCTION

Freshwater scarcity has become one of the most important worldwide issues of the twenty-first century. Although nearly 71% of the Earth's surface is covered by water, about 97% is saline in oceans and seas, while only nearly 3% is freshwater [1]. Of this 3% of freshwater, most is stored in glaciers and ice caps, and only a small fraction is available as surface water and groundwater directly accessible for human consumption [2]. Population growth, industrialization, expansion of agriculture, and climate change have intensified the depletion of freshwater resources, especially in arid and semi-arid areas. Therefore, it is crucial to develop

*CONTACT: Bholu Kumar, e-mail: bholu.kumar@poornima.edu.in

sustainable and decentralized desalination technologies.

The use of solar desalination, particularly solar stills, has become a sustainable and environmentally friendly alternative to conventional desalination techniques due to its low operational cost and minimal environmental impact. Conventional passive solar stills, despite their simplicity and low cost, suffer from low freshwater productivity because they depend heavily on available solar radiation, including poor nocturnal distillation due to a drop in basin water temperature after sunset.

In addition, these systems have limited operating time and cannot continuously produce fresh water because they lack efficient storage of excess thermal energy generated during peak sunshine hours. Therefore, researchers continue to explore ways to improve solar-still performance through design modifications or by integrating energy-storage materials.

Sahoo et al. [3] reported that conventional solar stills produce limited freshwater yield and are unable to generate water during nighttime, resulting in a daily yield of only 2-2.5 l/m²/day depending on basin water level and ambient conditions. Therefore, to enhance evaporation and condensation processes and overcome these limitations, several researchers have investigated modified basin designs and geometrical configurations to improve the thermal performance and productivity of solar stills.

Yadav and Sudhakar [4] reviewed the designs of domestic solar stills and reported that the thermal efficiency of a single-slope still remains between 25-35% and freshwater yield remains between 2-3 l/m²/day under normal climatic conditions, which hinders large-scale commercialization. Pathak et al. [5] studied solar stills coated with TiO_2 nanopaint and stated that there was about a 30-37% increase in productivity relative to standard paint. For single-slope stills, the maximum yield of 1811 ml/m² was recorded, while for double-slope stills it was 2488 ml/m² under the same environmental conditions [5]. The authors noted that this increase was due to greater solar absorption, better thermal conductivity, and faster evaporation because the water depth was lower.

Hussen et al. [6] modified the geometry of basins by conducting several experiments with 4 different basin designs and noted a range of 15-30% difference in productivity based on the basin design and angle of the basin. Abdullah et al. [7] noted that the use of turbulence and the incorporation of reflective surfaces, stepped basins, cooling systems, and solar tracking devices can significantly improve the evaporation rate. Under optimized conditions, these stills may be 1.5-2 times greater than the conventional stills [7]. Saravanakumar et al. [8] and D'Cotha et al. [9] reviewed stepped and inclined solar still configurations and noted a productivity increase of 15-35% compared with single-slope stills, attributed to a larger evaporation surface and better flow of condensed water. Optimized stepped configurations also demonstrated a thermal efficiency improvement of 5-10%. Modi and Jani [10] evaluated the performance of dual-slope solar stills, one with hollow fins and reported 18-25% more freshwater production than conventional dual-slope stills, attributable to a basin water temperature increase of 3-5 °C. Ghandourah et al. [11] enhanced a double-slope still using nanoparticle-coated wick materials and achieved productivity enhancement of nearly 20-30%, along with noticeable improvement in energy efficiency. Abdullah et al. [12] combined feed water preheating with PCM; they reported productivity rises of 25-40%, along with distillation extending 2-3 h post sunset. Senthil Kumar et al. [13] observed a 30% yield increase over a conventional triangular pyramid still with energy storage material. Benhammou and Sahli [14] observed that incorporating PCM, the energy efficiency of their system improved from 28% to ~35%, and the exergy efficiency was improved by 1-2%. Yousuf and Hassan [15, 16] experimentally demonstrated that latent heat storage increased daily distillate output by approximately 20-45% and improved exergy efficiency by nearly 1.5-2 times compared to passive stills. Banoqitah et al. [17] integrated nano-enhanced paraffin wax in a stepped still and reported productivity enhancement of around 35-50% due to improved thermal conductivity of PCM. Tuly et al. [18] performed energy, exergy, and exergoeconomic analyses of a nanoparticle-mixed PCM double-slope still and observed energy efficiency improvements of nearly 10-15% and better cost-per-litre performance. Nwosu et al. [19] demonstrated that paraffin wax integration extended distillation duration by about 2 h and improved yield by nearly 25–30%. Using nanofluid PCMs and wick-finned absorbers, Abdullah et al. [20] reported improvements in productivity of 30-45%. Tuly et al. [21] found that using PCM, fins, and wick structures increased the productivity of double-slope stills by almost 40 % relative to standard designs.

These studies show that integrating PCM can significantly improve performance, but most have used paraffin wax, nano-enhanced PCMs, or single-solar-still configurations [10, 13-19]. Moreover, the relative performance of single-slope and double-slope solar stills with the same eutectic organic PCM under similar operating conditions has not been adequately studied.

Hassan et al. [22] stated that using a PCM with a melting temperature of 45-60 °C improved the effective use of latent heat and the overall productivity of the system. Abo-Elfadl et al. [23] stated that system efficiency increased by 8–12% and that exergy efficiency improved under optimal conditions. In addition, Agrawal et al. [24] and Khanmohammadi and Khanmohammadi [25] showed that energetic and exergetic optimisation could improve the overall performance by 20-40% in comparison with the classical still structures.

Despite the reported energetic and exergetic improvements, the combined effect of solar still geometry, eutectic latent heat storage, and seasonal climate variation has received little attention. Therefore, this study investigates a eutectic mixture of palmitic acid and stearic acid with a phase-change temperature of about 55 °C to store thermal energy during high solar radiation and release it when solar intensity decreases. Hence, it is important to investigate this eutectic thermal storage approach in single- and double-slope solar stills to improve off-sunshine distillation and thermodynamic performance.

From the state of the art, many works have been done; however, few works have considered the combined effect of: (i) eutectic organic PCM with a melting temperature around 55 °C, (ii) the contrast between single- and double-slope configurations and (iii) seasonal real climatic conditions energetic and exergetic analysis. Thus, the main research gap is the lack of a systematic energetic and exergetic comparison between single- and double-slope solar stills integrated with the same palmitic acid–stearic acid eutectic PCM under different seasonal climatic conditions. The novelty of this work is the comparative experimental evaluation of CSSS, SSSEPCM, CDSSS, and DSSSEPCM at the same basin water depth of 10 mm under winter (December) and summer (May) conditions.

Therefore, this work investigates performance enhancements in single-slope and double-slope solar stills using an eutectic mixture of palmitic acid and stearic acid (phase-change temperature 55 °C). The study investigates freshwater productivity, energetic efficiency, and exergetic performance under winter (December) and summer (May) conditions. The results aim to support the design of efficient, sustainable, and thermodynamically balanced solar desalination systems in water-scarce areas.

2. MATERIALS AND METHODS

2.1 Preparation of Phase Change Material

Palmitic acid (PA) and stearic acid (SA), used as the base PCM materials, were procured from Fisher Scientific, India. The eutectic PCM was prepared using palmitic acid and stearic acid at a mass ratio of 64:36 wt%, as determined using Schröder's equation, and the preparation process is illustrated in Fig. 1. The resulting mixture exhibited a phase-change temperature of approximately 55 °C.

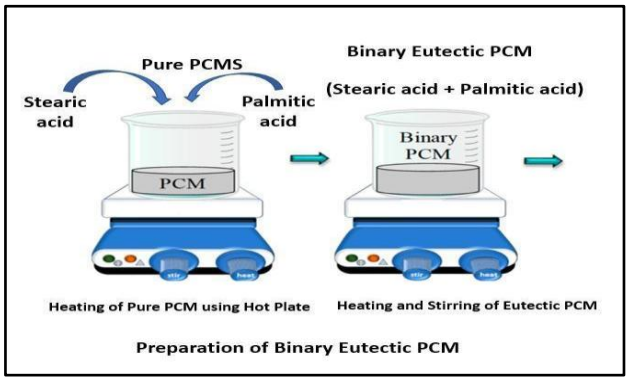

Fig. 1. Preparation of binary eutectic PCM

The required quantities of both fatty acids were accurately weighed using an analytical balance and placed in a clean borosilicate glass beaker. The mixture was heated on a temperature-controlled hot plate, and the temperature was gradually increased to 70-75 °C, which is above the melting points of both components, to ensure complete melting. Once fully molten, the mixture was stirred using a magnetic stirrer for about 30-40 min to achieve a homogeneous mixture and avoid phase separation. After sufficient mixing, the stirrer was turned off, and the molten eutectic mixture was allowed to cool to room temperature without disturbance until solidification was complete. The prepared eutectic PCM was then stored in an airtight container in a desiccator to avoid moisture absorption and contamination prior to further thermal characterization and experimental application.

The relevant thermophysical properties of the individual base PCMs and the prepared eutectic PCM are presented in Table 1.

Table 1. PCM Thermophysical properties

Property	Palmitic Acid (PA)	Stearic Acid (SA)	Eutectic PCM (PA = 64:36 wt%)
Chemical formula	$C_{16}H_{32}O_2$	$C_{18}H_{36}O_2$	Binary eutectic mixture
Molecular weight (g/mol)	256.42	284.48	-
Melting temperature (°C)	62-63	69–70	54–56
Latent heat of fusion (kJ/kg)	205-215	190-210	180-195
Specific heat capacity, solid (kJ/kg·K)	2.1	2	2.05
Specific heat capacity, liquid (kJ/kg·K)	2.3	2.2	2.25
Density, solid (kg/m³)	852	940	885
Density, liquid (kg/m³)	790	845	815
Thermal conductivity (W/m·K)	0.21	0.18	0.2
Thermal stability range (°C)	Up to 180	Up to 200	Up to 190
Supercooling tendency	Very low	Low	Negligible
Corrosiveness	Non-corrosive	Non-corrosive	Non-corrosive

2.2 Experimental Setup

This study evaluated the energetic and exergetic performance of single-slope and double-slope solar stills integrated with a eutectic phase-change material (PCM). Four unique designs for this experiment were created and tested under identical weather conditions:

- Conventional Single Slope Solar Still (CSSS);
- Single Slope Solar Still with Eutectic PCM (SSEPCM);
- Conventional Double Slope Solar Still (CDSSS);
- Double Slope Solar Still with Eutectic PCM (DSSSEPCM).

The experiments were performed in Bhopal, India, under similar outdoor climatic conditions to ensure the reliability and repeatability of the results. All solar stills were fabricated with the same dimensions using galvanised iron sheet (0.6 mm thickness) as the basin material and covered with a 4 mm thick transparent glass cover, as shown in Fig. 2.

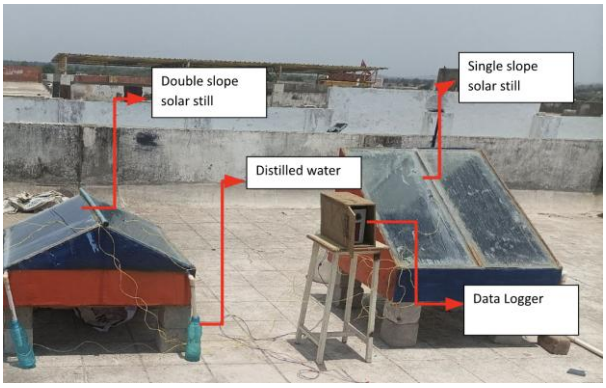

Fig. 2. Experimental set-up of single-slope and double-slope solar still with phase change material

The phase change material used in this experiment consists of a eutectic mixture of palmitic and stearic acid and has a melting point around 55 °C. This PCM was encapsulated and positioned below the basin liner to help collect and store thermal energy during periods of increased solar radiation and release it during nighttime periods and periods of low solar radiation.

2.3 Operating Conditions

All experiments were conducted at a constant basin water depth of 10 millimetres to ensure uniform comparison among configurations. The systems were tested under outdoor environmental conditions during the winter season (December) and the summer season (May). The experiments were performed from 09:00 h to 18:00 h, and night-time distillate production was measured separately to evaluate latent heat contribution.

2.4 Instrumentation and Measurements

The experimental parameters were measured with calibrated measuring instruments at an hourly interval. The solar radiation was measured using a pyranometer, and the basin water, inner glass cover and ambient temperatures were measured using K-type thermocouples. Freshwater yield was measured using a graduated measuring cylinder.

The specifications, measurement ranges, accuracies and uncertainty values of the instruments used in the present study are summarised in Table 2. All instruments were calibrated before the experiments to minimise measurement errors and to ensure reliability of the data recorded.

Table 2. Instrument detail

Instrument	Measured parameter	Range	Accuracy	Uncertainty
Pyranometer	Solar radiation	0–2000 W/m²	±10 W/m²	±1.5%
K-Type thermocouple	Basin water temperature	-50 to 200 °C	±0.5 °C	±0.8%
K-Type thermocouple	Glass cover temperature	-50 to 200 °C	±0.5 °C	±0.8%
Digital thermometer	Ambient temperature	-20 to 100 °C	±0.5 °C	±1.0%
Graduated measuring cylinder	Distillate yield	0–5000 ml	±5 ml	±0.5%
Stopwatch	Time measurement	0–24 h	±1 s	Negligible

3. PERFORMANCE EVALUATION

The thermodynamic, energy and exergy analysis of the investigated solar stills was performed based on the following assumptions:

- The system was assumed to be in a quasi-steady-state condition at each hourly measurement interval because the measured parameters were recorded and analysed at discrete hourly intervals.
- The basin water was assumed to be well mixed, and therefore its measured temperature was uniform throughout the basin due to the shallow water depth of 10 mm.
- The temperature of the inner glass cover was assumed to be spatially uniform for the heat-transfer calculations.
- Heat transfer through the side walls and bottom insulation was assumed to be negligible compared with the dominant heat transfer between the basin water, glass cover and surroundings because the still was adequately insulated.
- The thermophysical properties of water and construction materials were assumed to be constant within the temperature range of operation investigated.

3.1 Freshwater Yield

The freshwater yield was measured hourly for all configurations (CSSS, SSSEPCM, CDSSS, and DSSEPCM) at a water depth of 10 mm under identical climatic conditions. The distilled water collected from each still was measured using a calibrated measuring jar with a known least count. Hourly yield readings were recorded from 09:00 h to 18:00 h. Cumulative daily yield was obtained by summing the hourly distillate output for performance evaluation.

3.2 Energy Efficiency

Eq. 1 can be used to analyze the daily efficiency of a solar still in order to calculate how much its performance can be improved by implementing different modifications:

$$\eta_{\mathrm{d}} = \frac{\sum m_p \cdot h_{fg}}{A_b \cdot \sum I_d(t) \cdot 3600}, \quad (1)$$

where: η_d is the energy efficiency (%), m_p is the mass of distilled water (kg), h_{fg} is the latent heat of vaporization (kJ/kg), $I_d(t)$ is the solar radiation (W/m²), A_b is the basin area (m²), and t is the time interval (s).

3.3 Exergy Efficiency

When a thermal system reaches a condition of thermal equilibrium, its maximum performance is represented by its exergy.

The exergy through convection between water and the internal glass cover ($Ex_{c,w\,g}$) was calculated as:

$$Ex_{c,wg} = h_{c,wg} \cdot A_b \cdot (T_w - T_g) \cdot \left(1 - \frac{T_a}{T_w}\right), \quad (2)$$

where: $Ex_{c,wg}$ is the convective exergy (W), $h_{c,wg}$ is the convective heat transfer coefficient (W/m²·K), T_w is the basin water temperature (K), T_g is the inner glass cover temperature (K), T_a is the ambient temperature (K), and A_b is the basin area (m²).

The exergy through evaporation between water and the internal glass cover ($Ex_{e,wg}$) was calculated as:

$$Ex_{e,wg} = h_{e,wg} \cdot A_b \cdot (T_w - T_g) \cdot \left(1 - \frac{T_a}{T_w}\right), \quad (3)$$

where: $Ex_{e,wg}$ is the evaporative exergy (W), $h_{e,wg}$ is the evaporative heat transfer coefficient:

$$h_{e,wg} = 16.273 \cdot 10^{-3} \cdot h_{c,wg} \cdot \left[\frac{P_w - P_g}{T_w - T_g}\right], \quad (4)$$

where: P_w is the Partial vapour pressure on the water surface, P_g is the Partial vapour pressure on the inner glass.

The exergy through radiation between water and internal glass cover ($Ex_{r,wg}$) was calculated as:

$$Ex_{r,wg} = h_{r,wg} \cdot A_b \cdot (T_w - T_g) \cdot \left(1 - \frac{T_a}{T_w}\right), \quad (5)$$

$$h_{r,wg} = \varepsilon e \sigma \left[(T_w + 273)^2 + (T_g + 273)^2\right](T_w + T_g + 546), \quad (6)$$

where: $Ex_{r,wg}$ is the radiative exergy (W), $h_{r,wg}$ is the radiative heat transfer coefficients, and σ is the Stefan-Boltzmann constant.

The effective emissivity (ε_e) between water and the internal glass cover was given as:

$$\varepsilon_e = \left(\frac{1}{\varepsilon w} + \frac{1}{\varepsilon g} - 1\right) \quad (7)$$

where: ε_w is the emissivity of water, ε_g is the emissivity of the internal glass cover.

The leading mode of heat transfer in the solar still was determined by calculating the convective, evaporative, and radiative exergy fractions:

$$F_{c,wg} = \frac{Exc,wg}{Ex_t}, \quad (8)$$

$$F_{e,wg} = \frac{Exe,wg}{Ex_t}, \quad (9)$$

$$F_{r,wg} = \frac{Exr,wg}{Ex_t}, \quad (10)$$

where: $F_{c,wg}$ is the exergy fraction of convective heat transfer, E_{xt} is the total exergy power, $F_{e,wg}$ is the exergy fraction of evaporative heat transfer, and $F_{r,wg}$ is the exergy fraction of radiative heat transfer.

A mathematical Eq. 10 was used to calculate daily exergy efficiency:

$$\eta_{exe} = \frac{E_{x,out}}{E_{x,inp}} = \frac{Ex_{e,wg}}{E_{x,inp}} \quad (11)$$

where: η_{exe} is the exergy efficiency (%), $Ex_{,out}$ is the Exergy output, $Ex_{,inp}$ is the exergy input.

4. RESULT AND DISCUSSION

4.1 Performance Analysis During December

4.1.1 Meteorological Data During December

Fig. 3 shows the hourly variation in ambient temperature and solar radiation for December. Solar radiation increased steadily from 256 W/m² at 9:00 h to a maximum of 694 W/m² at 12:00 h, then gradually decreased to approximately 20 W/m² by 18:00 h. This decline continued through the afternoon because of the changing solar angle and reduced insolation typical of winter conditions. Similarly, the ambient temperature rose steadily from 19 °C at 9:00 h to a maximum of 28 °C at 14:00 h. The 2 h lag between the peak solar radiation (12:00 h) and the peak ambient temperature (14:00 h) can be attributed to the thermal inertia of the surrounding materials, which continue absorbing and releasing heat after peak irradiance. After 14:00 h, the ambient temperature declined, reaching approximately 19 °C by 18:00 h.

Meteorological conditions suggest moderately peaked solar irradiance and lower ambient temperatures, which are characteristic of winter months. These factors strongly affect the thermal behaviour and productivity of solar still systems. Low ambient temperature leads to a greater temperature difference between the basin water and the temperature of the glass cover; thus, condensation was higher.

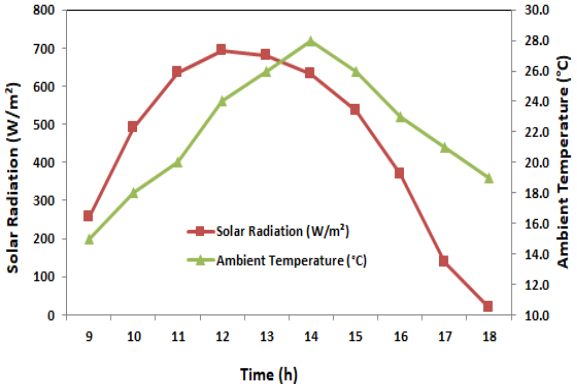

Fig. 3. Hourly variation of solar radiation and ambient Temperature in December

4.1.2 Temperature Distribution Analysis During December

Fig. 4 presents the hourly variation of the glass inner surface and basin water temperature for CSSS and SSSEPCM during December. The temperature of both the glass and water increases gradually from 9:00 AM to 1:00–2:00 PM as solar intensity and ambient temperature rise.

For the CSSS, the highest temperature on the inner glass surface reached around 49 °C from 13:00 to 14:00 h, while the basin water temperature peaked at 58 °C during the same hours. After 14:00 h, as solar radiation decreased, both temperature values declined gradually. For the SSSEPCM, temperatures recorded were comparatively higher. While the maximum glass inner surface temperature reached only 49°C, at 14:00 h the basin water temperature was recorded at 62°C. This higher water temperature in SSSEPCM is a result of the incorporation of the PCM, which captures thermal energy during the peak hours of sunshine and releases this energy slowly, improving thermal retention. Evidence of the PCM's thermal storage effect is the glass inner surface temperature of

SSSEPCM, which during the late hours (15:00 to 18:00) decreases more slowly than in CSSS. In December climatic conditions, SSSEPCM offers tangible improvements in thermal performance as compared to CSSS.

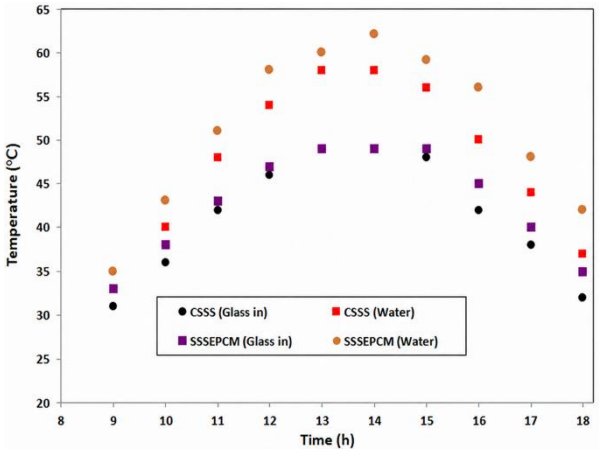

Fig. 4. Hourly variation of Glass inner temperature and water temperature for CSSS and SSSEPCM in December

Fig. 5 shows the hourly variation of the glass inner surface and basin water temperatures for DSSS and DSSSEPCM during December. Both glass and water temperatures increased gradually from 9:00 AM to 14:00 h as solar radiation increased, after which they declined.

For the DSSS, the temperature measured on the inner surface of the glass changed from 33 °C at 9:00 h to a maximum of 51 °C at 14:00 h. The water temperature in the basin also rose from 36 °C at 9:00 h to a maximum of 61 °C at 14:00 h. After the peak sunshine hours, temperatures started to decrease due to reduced solar intensity.

With the DSSSEPCM, temperatures were also higher throughout the day. The inner glass surface temperature at 14:00 h was 52°C, the highest measured, while the basin water temperature at the same hour was 66°C, also the highest measured. The higher thermal performance was attributed to the PCM's ability to store heat through latent heat and maintain elevated basin temperatures. Finally, during the late afternoon hours (15:00-18:00 h), the rate of temperature decrease with DSSSEPCM was lower than that of DSSS. This shows that the thermal storage and heat retention of DSSSEPCM was improved. Overall, the PCM's contribution to the double slope under the noted weather conditions in December was a significant contributor to its thermal performance.

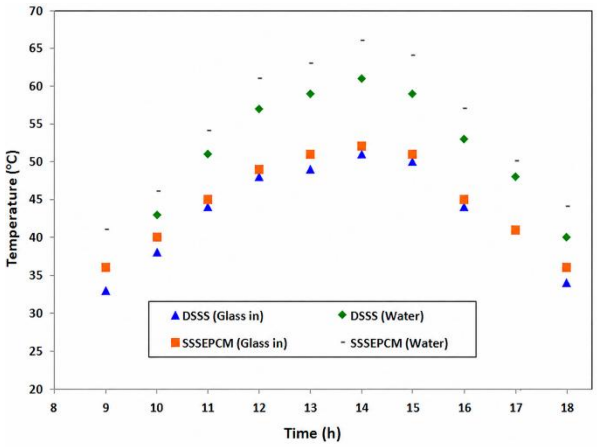

Fig.5. Hourly variation of Glass inner temperature and water temperature for CDSSS and DSSSEPCM in December

4.1.3 Yield Analysis During December

The hourly freshwater yield of different solar still configurations at 10 mm water depth during December is presented in Fig. 6. The systems considered include CSSS, SSSEPCM, CDSSS, and DSSSEPCM. From 9:00 onwards, all systems show a gradual increase in hourly yield, reaching a maximum between 13:00 and 14:00. This can be attributed to increased solar radiation and higher water temperature in the basin. Among the systems, DSSSEPCM achieved the highest peak hourly yield of 14:00 325 ml at 14:00, followed by 275 ml for SSSEPCM, 250 ml for CDSSS and 270 ml for CSSS.

Total daytime yield was 1415 ml for CSSS, 1770 ml for SSSEPCM, 1780 ml for CDSSS, and 2035 ml for DSSSEPCM. During nighttime, PCM-integrated systems showed significantly higher productivity due to stored latent heat release. Night yield was 160 ml for CSSS, 580 ml for SSSEPCM, 220 ml for CDSSS, and 750 ml for DSSSEPCM. Total daily yield was maximum for DSSSEPCM 2785 ml followed by 2350 ml for SSSEPCM, 2000 ml for CDSSS and 1575 ml for CSSS. Systems with PCM performed better because heat retention increased and evaporation decreased due to the absence of sunshine. In addition, systems with double slope have better utilization of the condensation surface area, thus yielding more.

Under winter climatic conditions, the use of PCM, the double-slope configuration, and lower water depth in the basin greatly improved freshwater productivity. The present results are consistent with previous studies [10, 13-15, 19], which also reported higher freshwater productivity after PCM integration. The similarity is mainly due to the latent heat storage capability of PCM, which

maintains basin water temperature and prolongs evaporation after sunset. Minor variations in productivity are attributed to differences in PCM type, solar still design, climatic conditions, and operating parameters.

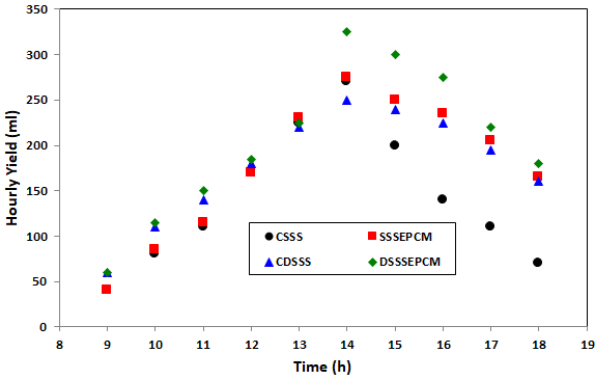

Fig. 6. Hourly yield of different types of solar stills in December

4.1.4 Energy efficiency Analysis During December

Fig. 7 shows the hourly energy efficiency of different solar still configurations at a water depth of 10 mm during December. Energy efficiency for all configurations began to increase in the same trend after 9:00 h.

As solar radiation and evaporation increased, efficiency reached maximum values around 14:00–15:00 h, corresponding to peak solar intensity and maximum basin water temperature.

For the CSSS, efficiency rose from 10.24% at 9:00 h to a maximum of 30.46% at 15:00 h. Also, for SSSEPCM, the efficiency rose from 13.24% to 34.46% at 15:00 h, indicating improved thermal utilization due to PCM integration. In addition, CDSSS efficiency exceeded that of CSSS, reaching 36.42% at 15:00 h. Of all configurations, DSSSEPCM had the highest efficiency, jumping from 20.33% at 9:00 to 42.65% at 15:00 h. After 15:00 h, as solar radiation decreased, efficiency gradually declined in all configurations. However, the PCM-bound systems performed better and maintained relatively higher efficiency later in the afternoon due to the release of stored thermal energy.

Integrating PCM and a double-slope design improves the thermodynamic efficiency of solar still systems in winter climatic conditions at 10 mm water depth. The DSSSEPCM configuration demonstrated the best thermal performance among all tested systems. The calculated energy efficiency trends agree with the results of Abdullah et al. [12], Benhammou and Sahli [14], and Yousef and Hassan [15], who also reported improved thermal performance upon incorporating PCM in solar stills. This similarity is primarily due to PCM's latent heat storage capability, which stores excess thermal energy during peak sunshine hours and releases it gradually during off-sunshine hours, maintaining higher basin water temperature and sustaining evaporation. The minor variations in the present work compared with previous studies are mainly due to differences in PCM properties, solar still geometry, basin water depth, climatic conditions, and operating parameters.

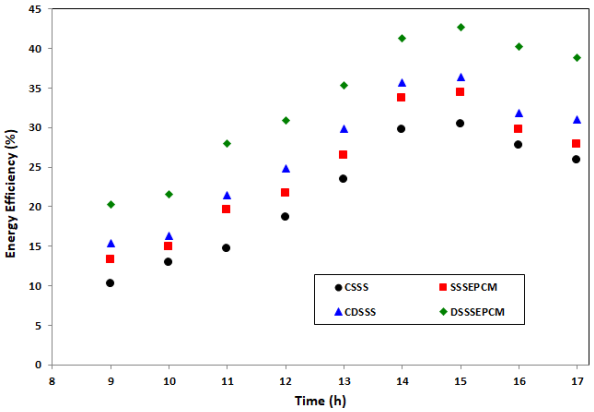

Fig. 7. Energy Efficiency of different types of solar still in December

4.1.5 Exergy Efficiency During December

The hourly exergy efficiency of different solar still configurations at 10 mm water depth during December is shown in Fig. 8. The configurations analyzed include CSSS, SSSEPCM, CDSSS, and DSSSEPCM. It is noted that the exergy efficiency also increased in the same manner starting from the morning hours, with the peak showing a similar pattern of maximum values to the energy efficiency at around 14:00–15:00 h for all configurations, due to peak solar radiation and maximum temperature difference that was in the basin water and the surroundings.

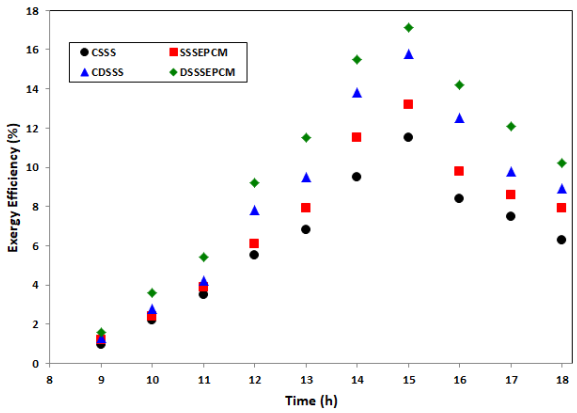

Fig. 8. Exergy Efficiency of different types of solar still in December

Exergy efficiency for CSSS improved from 0.95% at 9:00 h to 11.5% at 15:00 h. For SSSEPCM, efficiency improved from 1.2% to 13.2% at 15:00 h, reflecting improved heat storage and reduced thermodynamic inefficiencies. CDSSS performed consistently better, achieving 15.8% at 15:00 h.

Among all systems, DSSSEPCM had the highest exergy efficiency and performed best at all hours of the day. DSSSEPCM exergy efficiency increased from 1.6% at 9:00 h to a maximum of 17.1% at 15:00 h. After peak hours, all configurations' exergy efficiencies decreased. This was due to the decline of solar radiation and the temperature gradient. However, systems that had PCM had heat that was released in the afternoon and demonstrated exergy efficiencies that were higher than the rest of the configurations. Integrating PCM and double slope design improves the thermodynamic efficiency of the solar still systems in winter climatic conditions at 10 mm water depth. The DSSSEPCM configuration demonstrated the minimum exergy destruction and maximum useful energy utilization among all tested systems. The exergy efficiency trends obtained agree well with the results of Benhammou and Sahli [14], Yousef and Hassan [15], and Abo-Elfadl et al. [23], who reported enhanced exergy performance after adding PCM to solar stills. This similarity mainly stems from the PCM's effective latent heat storage and gradual heat release, which improve thermal energy utilisation and reduce exergy destruction during evaporation. The small differences from the results reported in the literature are mainly due to variations in PCM properties, solar still geometry, climate conditions, and operating parameters.

4.2 Performance Analysis During May

4.2.1 Meteorological Data During May

The hourly variation of solar radiation and ambient temperature during the month of May is shown in Fig 9. It is observed that solar radiation increased sharply from 600 W/m² at 9:00 h to a peak value of 950 W/m² at 13:00 h, indicating intense summer solar conditions. From 13:00 h to 18:00 h, a gradual decline in solar radiation was observed to 120 W/m². Between 9:00 am and 2:00 pm, the intensity of the solar radiation at the weather station's location caused a continuous increase in the air temperature; while between 9:00 am and 2:00 pm, the air temperature was between 30 °C and 44 °C; it was exactly 44 °C at 2:00 pm. For the radiant heat, a time lag in the ambient temperature is observed, this is due to the heat storage in the atmosphere and in the ground. After 2:00 pm, the air temperature decreases to 32 °C at 6:00 pm. The solar radiation in May and the air temperature are much greater than in the winter months and in other spring months due to the meteorological conditions. The increase in solar radiation (or solar intensity) increases the temperature of the water in the basin and increases the evaporation of the water in the solar stills. In the region of the stills, this leads to an increase in evaporation. But the water basin temperature and the glass cover temperature increase, causing a decrease in the difference in the condensation rate.

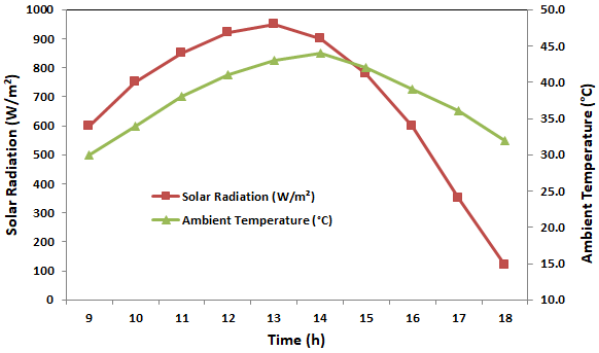

Fig. 9. Hourly variation of Solar radiation and ambient Temperature in May

4.2.2 Temperature Variation Analysis During May

Fig. 10 shows the hourly variation of the glass inner surface and basin water temperature for CSSS and SSSEPCM during May. Between 9:00 am and 2:00 pm, the onset of the summer season brought higher ambient temperatures and increased solar radiation.

For the CSSS, the highest recorded temperature on the glass inner surface was recorded at 14:00 h, as it peaked at 53 °C after having increased from 33 °C at 9:00 h. The basin temperature, however, peaked at 62 °C at 14:00 h, up from 35 °C. From 14:00 h, both temperatures slowed down in their increase due to the increase in solar intensity.

The SSSEPCM recorded even higher basin temperatures for the entire period. The basin surface water also recorded 64 °C at 14:00 h, while the maximum glass inner surface temperature recorded was 52 °C at 15:00 h. The temperature increase can be explained by the PCM's capacity to absorb heat (latent heat) at its peak, then release it after the peak period to regulate and maintain the water temperature in the basin. Fig. 10 also shows that during the last 3 h of the period (15:00-18:00), SSSEPCM recorded higher temperatures than CSSS, indicating better heat retention and reduced

thermal losses. In general, under the climatic conditions of May, SSSEPCM has better thermal performance than CSSS.

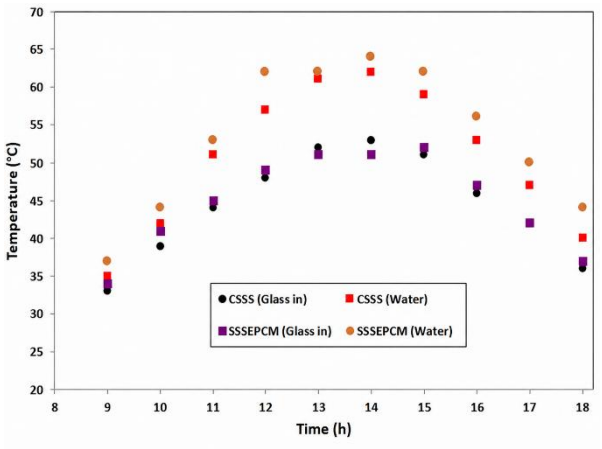

Fig. 10. Hourly variation of Glass inner temperature and Water temperature for CSSS and SSSEPCM in May

Fig. 11 shows the hourly variation of glass inner surface and basin water temperature for DSSS and DSSSEPCM during May. Temperatures increased steadily from 9:00 AM to 14:00 h due to high solar radiation and elevated ambient temperatures typical of summer. For the DSSS, the glass inner surface temperature increased from 34 °C at 9:00 h to a maximum of 52 °C at 14:00 h. The basin water temperature rose from 40 °C to a peak value of 63 °C at 14:00 h. After peak sunshine hours, both temperatures gradually declined as solar intensity decreased.

For the DSSSEPCM, glass temperatures reached 53 °C at 14:00 h and basin water temperatures reached 69 °C at the same time. The increase in water temperature is due to the PCM's latent heat storage. It stores heat during peak radiation and then releases it to the basin, keeping temperatures high late in the afternoon. Also, the period 15:00-18:00 h showed slower declines in DSSSEPCM compared to DSSS, indicating improved heat retention and storage. From the incorporation of PCM with the double slope configuration, the solar still shows better thermal performance and is expected to provide more freshwater due to higher basin temperatures.

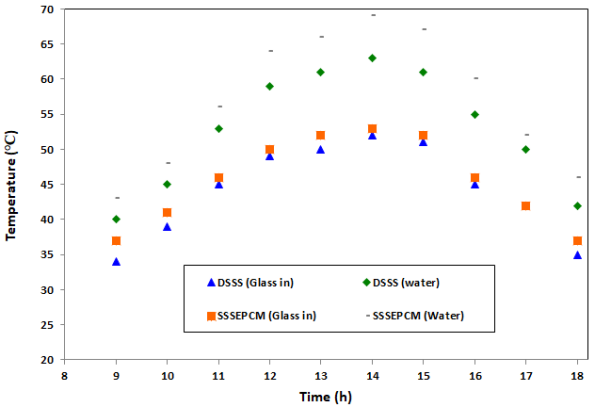

Fig. 11. Hourly variation of Glass inner temperature and Water temperature for DCSSS and DSSSEPCM in May

4.2.3 Yield Analysis During May

Fig. 12 shows the hourly freshwater yield of different solar still configurations at 10 mm water depth during May. Under summer conditions, maximum solar radiation and basin water temperature contribute to a peak hourly yield around 14:00 h. As hourly yield increased, DSSSEPCM recorded the maximum value of 345 ml at 14:00 h, followed by SSSEPCM at 310 ml, and CDSSS and CSSS at 290 ml each.

The total daytime yield was found to be 1645 ml for CSSS, 1995 ml for SSSEPCM, 2085 ml for CDSSS, and 2320 ml for DSSSEPCM. At night, PCM-integrated systems showed significantly higher productivity due to stored latent heat release. Night yield was 190 ml for CSSS, 610 ml for SSSEPCM, 270 ml for CDSSS, and 810 ml for DSSSEPCM. The total daily yield for DSSSEPCM was 3130 ml, SSSEPCM was 2605 ml, CDSSS was 2355 ml, and CSSS was 1835 ml. PCM-based systems enhanced productivity due to sustained evaporation and thermal retention. The double-slope configuration also yields more overall freshwater because it has a larger effective condensation area. Overall, the results indicate that at 10 mm water depth under summer climatic conditions, the DSSSEPCM configuration demonstrates superior performance among all tested systems. The productivity enhancement observed in this work agrees with reports by Abdullah et al. [12], Yousef and Hassan [15], Nwosu et al. [19], and Tuly et al. [21] on improved freshwater production and longer distillation periods using PCM-based thermal energy storage. These results are similar because the PCM absorbed excess thermal energy during periods of high solar radiation and released it when solar intensity decreased, maintaining basin water temperature and the evaporation process. The magnitude of productivity enhancement differs

from previous studies because of differences in PCM type and phase-change temperature, solar still geometry, basin water depth, climatic conditions, and heat-transfer enhancement methods such as nanoparticles, fins, and wicks [15, 16, 18, 19]. The enhanced performance of DSSSEPCM in the present study is due to the combined effect of the double slope configuration and latent heat storage provided by the palmitic acid–stearic acid eutectic PCM, especially during the off-sunshine hours.

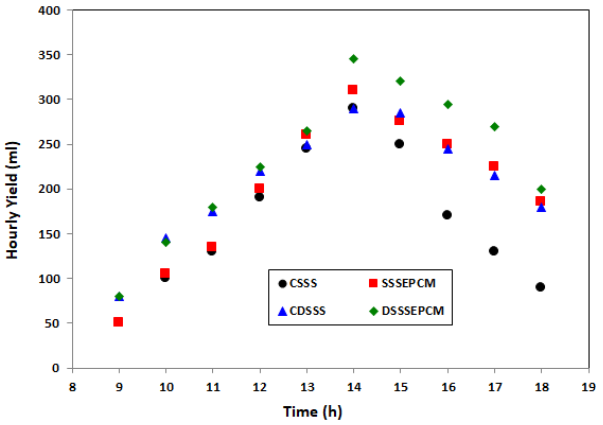

Fig. 12. Hourly yield of different types of solar still in May

4.2.4 Energy Efficiency Analysis During May

The hourly energy efficiency of different solar still configurations at 10 mm water depth during May is shown in Fig. 13. The systems analyzed include CSSS, SSSEPCM, CDSSS, and DSSSEPCM. From 14:00 h to 15:00 h, all configurations reached their peak for energy efficiency due to increasing solar radiation and evaporation rate. By 15:00 h, CSSS achieved 37.7% efficiency, up from 16.2% at 09:00 h. With enhanced thermal storage, SSSEPCM improved performance to a 40.6 % peak at 15:00 h, up from 18.5%. CDSSS surpassed CSSS, with a peak of 45.3% at 15:00 h.

DSSSEPCM showed the best overall daily performance, starting at 24.4% at 09:00 h and peaking at 49.3% at 15:00 h. After 15:00 h, all systems gradually decreased in performance due to reduced solar radiation, but PCM-based systems continued to outperform because they released stored thermal energy. PCM and double-slope solar still configurations showed substantial improvements in still energy efficiency during summer at 10 mm water depth. The DSSSEPCM configuration demonstrated the best thermal performance among all tested systems. The increase in energy efficiency is mainly due to the latent heat storage property of the eutectic PCM, which stores excess thermal energy during peak solar radiation and releases it gradually during off-sunshine hours. This continuous heat release keeps the water in the basin at a higher temperature, extending evaporation and improving the utilisation of absorbed solar energy, leading to higher energy efficiency. Abdullah et al. [12], Benhammou and Sahli [14], Yousef and Hassan [16], and Tuly et al. [18] reported similar results. These small variations compared with previous studies mainly reflect differences in PCM properties, solar still geometry, climatic conditions, and operating conditions.

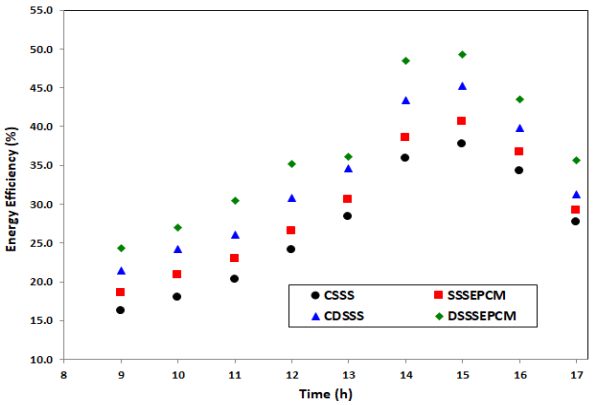

Fig. 13. Energy Efficiency of different types of solar still in May

4.2.5 Exergy Efficiency During May

The hourly variation of exergy efficiency for different solar still configurations at 10 mm water depth during May is shown in Fig. 14. The systems analyzed include CSSS, SSSEPCM, CDSSS, and DSSSEPCM. Exergy efficiency increased steadily from morning hours as solar radiation and basin water temperature rose. For CSSS, efficiency increased from 1.3% at 9:00 h to a maximum of 13.5% at 15:00 h, then gradually declined to 7.2% at 18:00 h. In the case of SSSEPCM, efficiency rose from 1.56% at 9:00 h to 14.9% at 15:00 h. At 15:00 h, CDSSS configurations had higher thermodynamic efficiencies than single-slope configurations, with a maximum of 17.5%. However, DSSSEPCM had the best exergy efficiency for the entire day. It increased from 2.85% at 9:00 h to a maximum of 18.6% at 15:00 h and remained relatively high (16.2% at 16:00 h and 14.2% at 17:00 h) even as solar intensity declined.

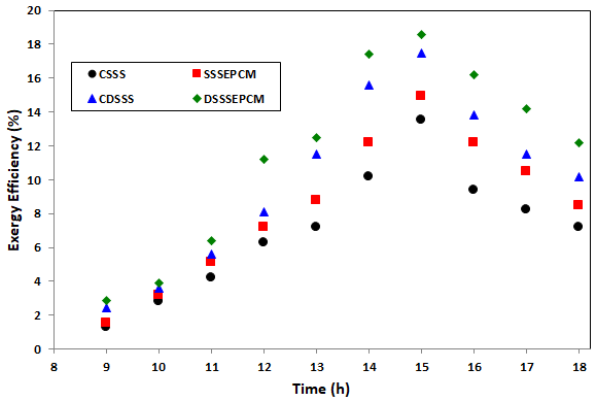

Fig. 14. Exergy Efficiency of different types of solar still in May

The results clearly indicate that the integration of PCM and double-slope design significantly reduces exergy destruction and improves useful energy utilization under high solar radiation conditions of May. The maximum exergy efficiency in May (18.6%) is comparatively higher than in winter conditions, mainly due to elevated ambient temperature and enhanced evaporation rate. The thermodynamic difference between the energy and exergy efficiencies leads to a lower value for the exergy efficiency compared to the energy efficiency. The energy analysis considers the amount of energy used in the distillation process, whereas the exergy analysis considers the quality of the energy and its maximum potential for useful work.

Thermodynamic irreversibilities in solar stills arise from heat transfer across finite temperature differences, evaporation and condensation, and heat losses to the surroundings, leading to exergy destruction.

Moreover, the relatively low operating temperature of the basin water limits the work potential of the supplied solar energy. Consequently, only a fraction of the available energy can be converted into useful exergy, resulting in considerably lower exergy efficiency than energy efficiency.

5. SEASONAL COMPARISON RESULTS

A comparative seasonal analysis indicates that all solar still configurations performed better in May (summer) than in December (winter) because of higher solar radiation intensity and elevated ambient temperatures. The total yield increased from 1575 ml to 1835 ml for CSSS, from 2350 ml to 2605 ml for SSSEPCM, from 2000 ml to 2355 ml for CDSSS, and from 2785 ml to 3130 ml for DSSSEPCM when shifting from winter to summer operation as shown in Fig. 15. The enhancement in summer productivity was accompanied by higher peak energy efficiencies, which increased from 42.65% in December to 49.3% in May for DSSSEPCM. Under high-insolation conditions, maximum exergy efficiency improved from winter to summer, from 17.1% to 18.6%. This reflects better thermodynamic utilization of solar energy.

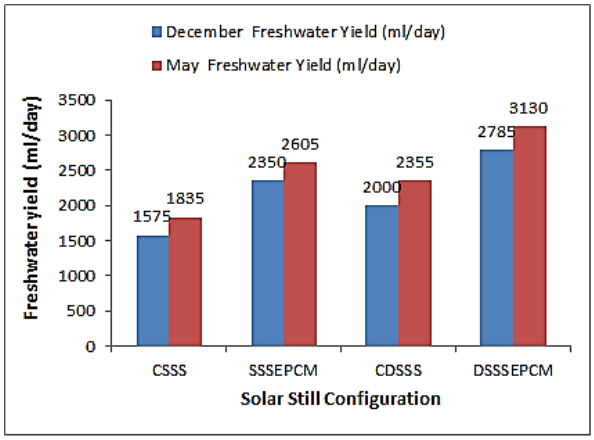

Fig. 15. Seasonal comparison of freshwater yield of different solar still configurations

While solar energy capture is less efficient in December, the use of latent heat storage (PCM) in the solar stills allows capture of energy during the day and release of that stored energy to extend energy capture during the evening and night hours; thus, during December, PCM ensured more equal yields in December as day night and evening yields, and therefore basin temperatures, stabilized more evenly. This is coupled with PCM in winter holding and capturing basin temperature and providing more nighttime yields than without PCM. This resulted in PCM capture improving winter performance with respect to night yields and basin temperatures more than counteracting the winter capture losses in summer. Therefore, while the summer season of higher solar capture provided more absolute production and efficiency than the winter season, the use of PCM solar stills provided better performance in summer and winter balance and performance than other solar stills. The seasonal performance observed in the present study is in agreement with earlier investigations [10, 12-16], which indicated better productivity and efficiency during summer due to higher solar radiation and ambient temperature. The small difference in performance is mainly due to differences in climatic conditions, PCM properties and solar still geometry.

6. CONCLUSION

This experimental investigation evaluated the thermal and thermodynamic performance of single-slope and double-slope solar stills, with and without eutectic PCM integration, at a constant basin water depth of 10 mm in the winter (December) and summer (May) seasons.

Of all configurations, the DSSSEPCM performed best. The maximum total freshwater yields were much greater than those of the other conventional solar stills, with 2785 ml recorded in December and 3130 ml in May.

In terms of energy efficiency, DSSSEPCM recorded 42.65% in December and 49.3% in May. Peak exergy efficiency in December and May was 17.1% and 18.6%, respectively.

For the combined solar stills, the PCM-integrated double-slope solar stills system was the most productive and efficient in terms of thermodynamic performance.

This study on solar distillation combined with PCM systems also stands out for its reliability, sustainability, and seasonal versatility in generating freshwater in regions with limited water resources and high solar potential. The proposed DSSSEPCM system provides an easy and energy-efficient solution for sustainable decentralised freshwater production, especially in arid and remote areas with plentiful solar energy and limited access to potable water.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

REFERENCES

[1] The United Nations World Water Development Report 2016: Water and Jobs. *UNESCO*, 2016. https://unesdoc.unesco.org/ark:/48223/pf0000243938 (Accessed: 10 March 2026)

[2] Where is Earth's Water? *U.S. Geological Survey*, 2018. https://www.usgs.gov/special-topics/water-science-school/science/where-earths-water (Accessed: 10 March 2026)

[3] B.B. Sahoo, N. Sahoo, P. Mahanta, L. Borbora, P. Kalita, U.K. Saha, Performance Assessment of a Solar Still Using Blackened Surface and Thermocol Insulation. *Renewable Energy*, 33, 2008: 1703-1708. https://doi.org/10.1016/j.renene.2007.09.009

[4] S. Yadav, K. Sudhakar, Different Domestic Designs of Solar Stills: A Review. *Renewable and Sustainable Energy Reviews*, 47, 2015: 718-731. https://doi.org/10.1016/j.rser.2015.03.064

[5] P.K. Pathak, B. Kumar, R. Agrawal, Enhanced Thermal Performance Analysis of Single and Double Slope Solar Stills Coated With TiO_2 Nanoparticle-Infused Nanopaint. *Applied Engineering Letters*, 10(3), 2025: 146-159. https://doi.org/10.46793/aeletters.2025.10.3.3

[6] H.M. Hussen, M.M. Younes, W.H. Alawee, A.S. Abdullah, S.A. Mohammed, T.E.M. Atteya, F. Abbas, Z.M. Omara, An Experimental Comparison Study between Four Different Designs of Solar Stills. *Case Studies in Thermal Engineering*, 44, 2023: 102841. https://doi.org/10.1016/j.csite.2023.102841

[7] A.S. Abdullah, H. Panchal, W.H. Alawee, Z.M. Omara, Methods Used to Improve Solar Still Performance with Generated Turbulence for Water Desalination—Detailed Review. *Results in Engineering*, 19, 2023: 101251. https://doi.org/10.1016/j.rineng.2023.101251

[8] R. Saravanakumar, J. Venugopal, C. Udagani, V. Thiyagarajan, S.K. Nandha Kumar, L. Karnan, A.E. Kabeel, B. Madhu, R. Sathyamurthy, A Mini Review on Recent Advancements in Inclined Solar Still. *Energy Reports*, 8, 2022: 641-645. https://doi.org/10.1016/j.egyr.2022.09.174

[9] J.S. D'Cotha, P. Sajeesh, P.R. Suresh, J. Jithu, Inherent Configuration Characteristics Altering the Distillate Enhancement of Passive Stepped Solar Still: A Review. *Journal of King Saud University - Engineering Sciences*, 36(8), 2024: 684-693. https://doi.org/10.1016/j.jksues.2021.10.001

[10] K. Modi, H. Jani, Experimental and Theoretical Assessment of Dual-Slope Single-Basin Solar Still with the Circular Cross-Sectional Hollow-Fins. *Cleaner Engineering and Technology*, 4, 2021: 100231. https://doi.org/10.1016/j.clet.2021.100231

[11] E.I. Ghandourah, A. Sangeetha, S. Shanmugan, M.E. Zayed, E.B. Moustafa, A. Tounsi, A.H. Elsheikh, Performance Assessment of a Novel Solar Distiller with a Double Slope Basin Covered by Coated Wick with Lanthanum Cobalt Oxide Nanoparticles. *Case Studies in Thermal Engineering*, 32, 2022: 101859. https://doi.org/10.1016/j.csite.2022.101859

[12] A.S. Abdullah, L. Hadj-Taieb, M.M. Hikal, Z.M. Omara, M.M. Younes, Enhancing a Solar Still's Performance by Preheating the Feed Water and Employing Phase-Change Material. *Alexandria Engineering Journal*, 77, 2023: 395-405. https://doi.org/10.1016/j.aej.2023.07.002

[13] S. Senthil Kumar, S.D. Uma Mageswari, M. Meena, V. Nagaraju, B. Yakkala, D. Vinod, D. Mageshbabu, B. Madhu, R. Sathyamurthy, Effect of Energy Storage Material on a Triangular Pyramid Solar Still Operating with Constant Water Depth. *Energy Reports*, 8, 2022: 652-658. https://doi.org/10.1016/j.egyr.2022.10.203

[14] M. Benhammou, Y. Sahli, Energetic and Exergetic Analysis of a Sloped Solar Still Integrated with a Separated Heat Storage System Incorporating Phase Change Material. *Journal of Energy Storage*, 40, 2021: 102705. https://doi.org/10.1016/j.est.2021.102705

[15] M.S. Yousef, H. Hassan, Energetic and Exergetic Performance Assessment of the Inclusion of Phase Change Materials (PCM) in a Solar Distillation System. *Energy Conversion and Management*, 179, 2019: 349-361. https://doi.org/10.1016/j.enconman.2018.10.078

[16] M.S. Yousef, H. Hassan, An Experimental Work on the Performance of Single Slope Solar Still Incorporated with Latent Heat Storage System in Hot Climate Conditions. *Journal of Cleaner Production*, 209, 2019: 1396-1410. https://doi.org/10.1016/j.jclepro.2018.11.120

[17] E. Banoqitah, R. Sathyamurthy, E.B. Moustafa, M. Fujii, P. Sudalaimuthu, F. Djouider, A.H. Elsheikh, Enhancement and Prediction of a Stepped Solar Still Productivity Integrated with Paraffin Wax Enriched with Nano-Additives. *Case Studies in Thermal Engineering*, 49, 2023: 103215. https://doi.org/10.1016/j.csite.2023.103215

[18] S.S. Tuly, M.S. Islam, R. Hassan, B.K. Das, M.R.I. Sarker, Investigation of a Modified Double Slope Solar Still Integrated with Nanoparticle-Mixed Phase Change Materials: Energy, Exergy, Exergo-Economic, Environmental, and Sustainability Analyses. *Case Studies in Thermal Engineering*, 37, 2022: 102256. https://doi.org/10.1016/j.csite.2022.102256

[19] E.C. Nwosu, G.N. Nwaji, C. Ononogbo, I. Ofong, P.C. Nwadinobi, N.V. Ogueke, E.E. Anyanwu, Numerical and Experimental Study of a Single-Slope Double-Effect Solar Still Integrated with Paraffin Wax. *Energy Nexus*, 8, 2022: 100155. https://doi.org/10.1016/j.nexus.2022.100155

[20] A.S. Abdullah, Z.M. Omara, F.A. Essa, U.F. Alqsair, M. Aljaghtham, I.B. Mansir, S. Shanmugan, W.H. Alawee, Enhancing Trays Solar Still Performance Using Wick Finned Absorber, Nano-Enhanced PCM. *Alexandria Engineering Journal*, 61(12), 2022: 12417-12430. https://doi.org/10.1016/j.aej.2022.06.033

[21] S.S. Tuly, M.S. Rahman, M.R.I. Sarker, R.A. Beg, Combined Influence of Fin, Phase Change Material, Wick, and External Condenser on the Thermal Performance of a Double Slope Solar Still. *Journal of Cleaner Production*, 287, 2021: 125458. https://doi.org/10.1016/j.jclepro.2020.125458

[22] H. Hassan, M.S. Yousef, M. Fathy, Productivity, Exergy, Exergoeconomic, and Enviroeconomic Assessment of Hybrid Solar Distiller Using Direct Salty Water Heating. *Environmental Science and Pollution Research*, 28, 2021: 5482-5494. https://doi.org/10.1007/s11356-020-10803-2

[23] S. Abo-Elfadl, M.S. Yousef, H. Hassan, Energy, Exergy, Economic and Environmental Assessment of Using Different Passive Condenser Designs of Solar Distiller. *Process Safety and Environmental Protection*, 148, 2021: 302-312. https://doi.org/10.1016/j.psep.2020.10.022

[24] R. Agrawal, K.D.P. Singh, Performance evaluation of double slope solar still augmented with binary eutectic phase change material and steel wool fibre. *Sustainable Energy Technologies and Assessments*, 48, 2021: 101597. https://doi.org/10.1016/j.seta.2021.101597

[25] S. Khanmohammadi, S. Khanmohammadi, Energy, Exergy and Exergo-Environment Analyses, and Tri-Objective Optimization of a Solar Still Desalination with Different Insulations. *Energy*, 187, 2019: 115988. https://doi.org/10.1016/j.energy.2019.115988

© 2026 by the authors. This work is licensed under a Creative Commons Attribution-Non Commercial 4.0 International License (CC BY-NC 4.0).