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Performance analysis of single-Basin single slope solar water still system integrated with phase change material and porous structure

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Abstract

This work aims to experimentally investigate the improvement in the performance and water productivity of a single-basin single-slope solar water distiller system by adding a porous structure (stones) and phase change material (PCM) above the basin surface. To explore the impact of adding a porous structure and PCM, two models are tested. The modified model that uses a porous structure and PCM is called (MSD-FSP), whereas the normal model is called (SD-F). Both systems include fins fixed above the absorber surface. A paraffin wax filled inside tubes as PCM is used with the MSD-FSP model. The experiments are conducted in Mosul City, Iraq, during November and December 2023. The MSD-FSP model is tested with only PCM and PCM with stones. The findings obtained from MSD-FSP and SD-F are compared under various water depths. The results showed that the MSD-FSP model is more effective than the SD-F model, where the performance of the MSD-FSP is higher than the SD-F by 31% for 30 mm water depth and 27% for 50 mm water depth. The findings also observed that the water productivity of the MSD-FSP model is larger than that of the SD-F model by 35% (for 30 mm water depth) and 28% (for 50 mm water depth). The findings indicated that the highest water temperature and water productivity are achieved while using the MSD-FSP model, and these values are equal to 49.8°C and 0.81 kg/m^2 at a water depth of 30 mm. The results confirm that using a porous structure (stones) and PCM has considerable impacts on heat exchange, evaporation rate, and heat transfer and hence, improves system performance.

KEYWORDS

phase change material, solar water distiller, stones, thermal performance, water depth, water productivity

Abbreviations: CSS, Conventional solar-still; DPD, Developed Pyramid-Distiller; DSD, dome-shaped solar distiller; FFS, fountain seawater feed supply; FPC, Flat Plate Collector; GWCA, great wall construction algorithm; LHSM, Single basin of solar still having PCM; LSTM, long short-term memory; MHSS, modified hemispherical solar still; MSD-FSP, Modified Solar distiller having fins, PCM and porous structure; NCPCM, PCM integrated with CuO nanoparticles; PCM, Phase Change Material; PCST-TSS, Parabolic Concentrater Solar Tracking Systems; RDSD, Reference dome-shaped solar distiller; SD, Solar Distiller; SD-F, Normal Solar distiller having fins; SHSM, Sensible heat storage materials; SS, Solar Still; TDS, Total dissolved solid; THSS, traditional hemispherical solar still; TPD, Traditional Pyramid-Distiller.

1 | INTRODUCTION

Shortages of freshwater and energy, along with global warming, represent the most significant threats to our world.[1,2] Fossil fuels will eventually be depleted, whether it happens now or in the future. On the other hand, fossil fuels contribute to environmental pollution and exacerbate global warming; thus, the transitioning to cleaner and more sustainable energy sources is crucial for mitigating these issues.[3–6] Solar distillers are an excellent choice for producing freshwater as they do not cause pollution and are cost-effective. The distiller structure merely needs sunlight to fall upon it.[7] Distillers are designed with a basin for holding seawater that is to be heated, as well as a condensation cover to condense the water vapor.[8–10] Solar desalination systems have garnered significant attention due to their numerous advantages for the environment and reduced fuel costs. These systems are highly regarded for their simplicity, affordability, and ease of manufacturing using materials readily available locally. Additionally, their environmental sustainability and low costs of maintenance contribute to their popularity. However, despite these favorable attributes, they suffer from low production.[11] Solar distillers (SD) have experienced numerous advancements in design and enhancement techniques to achieve optimal freshwater productivity, thermal energy efficacy, and cost-effectiveness.

The variety of designs and modifications available has contributed to the ongoing evolution of solar distillation technology, as there are numerous designs and modifications: pyramid SD;[12] Saravanan and Murugan,[13] double slope SD,[14,15] tubular SD,[16,17] inclined SD.[18,19] Further, the SD system's performance can be improved by the addition of fins, reflectors,[20,21] wick materials,[22] nanofluids,[14,15,23,24] PCM,[25–29] corrugated absorber plate[30,31] and external condenser.[30–32] The implementation of these techniques has improved the productivity and efficiency of SD systems. The productivity of the SD system is predominantly influenced by solar radiation. Numerous studies have been conducted to investigate the relationship between solar radiation and the productivity of the SD system. The results of these studies have consistently demonstrated that the increase in incident solar radiation enhances productivity, and this can be attributed to the rise in temperature differential between the water and the transparent cover.[33,34] Diabil[35] investigated the potential of using aluminum foils on the inner surfaces of the single-slope single-basin SD system. By minimizing heat loss through the walls, more solar radiation could be effectively utilized as it was redirected toward the distiller basin. Shmroukh and Ookawara[36] enhanced the performance of the single-slope distillation system by incorporating copper fins, a stepped basin, and internal reflectors alongside external reflectors. The results indicated that the upgraded distillation system achieved a remarkable 129% improvement in productivity while maintaining a high thermal efficiency of 63%. Supplying distillers with wick materials has proven to be a viable strategy for enhancing both the yield and utilization of solar energy.[14,15] conducted a study on three proposed enhancements to the traditional pyramid distiller (TPD) to improve its efficiency. The first enhancement, known as the developed pyramid distiller (DPD), utilizes v-corrugated absorbers to expand the evaporation surface area. The second enhancement, DPDW, integrates wick materials to reduce the feed water rate, thereby boosting productivity. The third enhancement, DPDW+CuO, introduces copper oxide nanofluid to enhance thermal conductivity and absorptivity. The findings revealed that the modified systems exhibited significant enhancements, with total freshwater productivity increasing by 28.38%, 45%, and 72.95% in comparison to the TPD. The greatest increment in daily energy efficiency was demonstrated by the DPDW+CuO system.

Negi et al.[37] conducted an experimental study on the performance of conventional solar still (CSS), horizontal wick SS with flat plate collectors (FPC) and basin-tilting wick SS at 30° integrated with FPC under similar atmospheric conditions. The study included two scenarios: scenario-1 compares the horizontal wick SS with FPC to CSS, whereas scenario-2 compares the tilt wick SS at 30° integrated with FPC to the horizontal wick SS. The findings indicated that the total distillate production was 3.216 kg/m^2 per day and 2.894 kg/m^2 per day, respectively. Furthermore, the horizontal wick SS exhibited higher cumulative and day efficiency by 16.6% and 12.1%, respectively. Recently, thermal storage techniques have emerged as the first choice to improve the efficiency of the SD system. The types of thermal storage that fall into this category are known as latent heat storage materials, for example, (glycols, eutectic salts, fatty esters, fatty acids and paraffin wax) or sensible heat storage materials, for example, (gravel, sand, rocks, granite and water) (Jamshideasli[38]). Modi and Nayi[39] presented the performance of square pyramid SS by focusing on the action of forced evaporation, forced condensation, and thermal storage material. The results confirmed that the SS incorporating forced evaporation and thermal storage at a water depth of 3 cm emerged as the most productive and efficient option. Elashmawy[40] investigated the application of locally sourced gravel in tubular SS that incorporates a parabolic concentrator solar tracking system (PCST-TSS). The findings indicated that there is significant potential for gravel use in PCST-TSS, presenting additional avenues for enhancing performance. With gravel, the thermal efficiency and productivity are increased by 36.34% and 4.51 L/m^2 per day, respectively, while the PCST system boosts the TSS productivity by 890.4% and the efficiency by 27.33%.

Manoj et al.[41] investigated the efficiency of conventional single-slope passive solar distiller (CSS) integrated with paraffin-based phase change material (PCM) as LHSM and nano-PCM (n-PCM) for daily freshwater production. They designed and constructed three SS systems: one is left unchanged, the second is integrated with PCM, and the third is combined with n-PCM. The results revealed that the integration of PCM and n-PCM increased freshwater production by 51.22% and 67.07%, respectively. Kateshia and Lakhera[42] evaluated the efficiency of a single basin SS by utilizing PCM as LHSM with and without using pin fins. The investigation covered three scenarios: traditional, with PCM, and with PCM plus pin fins. The findings discovered that the overall productivity increased by 24% in Case II and by 30% in Case III. Furthermore, the highest energy and exergy efficiencies were recorded in Case III, establishing the SS equipped with PCM and pin fins as a cost-effective alternative system.

The nanoparticles exhibit a wide range of applications in SS systems and enhance the heat transfer process within the basin. The nanofluids (NFs) are known for their exceptional heat absorption capabilities, superior thermal conductivities, and efficient heat transfer coefficients. Many scholars have employed nanomaterials as an innovative approach to improve the overall performance of SS systems. Parsa et al.[43] carried out an experimental investigation on two SD systems at Mount Tochal and in Tehran City by utilizing silver NF for its thermal conductivity, optical characteristics, and antibacterial effects.

The findings indicated that altitude markedly influenced the systems' performance, with the silver NF being the most impactful factor. The system located at Tochal demonstrated superior energy efficiency, whereas the systems in Tehran exhibited an increment in the overall energy efficiency by 106% and 196%, respectively. Thakur et al.[44] carried out an experimental study in Jaipur, India, to compare the efficiency of simple and nano-fluid SS systems. The glass covers of the SS were coated with nano-paint, which led to a higher rate of vaporization and increased yield productivity. The research indicated that the simple SS yielded 4.47 L of water at a water depth of 1 cm, whereas the NF and nano-paint-enhanced SS produced 5.56 L at the same water depth.

Hammad et al.[45] presented a novel design of a dome-shaped solar distiller (DSD) featuring a stepped conical basin and multiple trays aimed at enhancing evaporation and exposure. The system employed a fountain seawater feed supply (FFS) to minimize the thickness of saltwater on the trays. A PCM integrated with CuO nanoparticles (NCPCM) is utilized to boost nighttime production. Three variations of DSDs are evaluated: one incorporating both (DSD-FFS + NCPCM), another with solely the fountain feed (DSD-FFS), and a reference distiller (RDSD). The findings indicated that DSD-FFS + NCPCM achieved a yield of 7.21 kg/day/m^2, while DSD-FFS yielded 6.84 kg/day/m^2, both significantly surpassing the RDSD's output of 4.44 kg/day/m^2. The efficiency and cost per kilogram of distillate showed marked improvements for the new distillers in comparison to the RDSD. Elsheikh et al.[46] developed a new solar distiller with a unique prismatic shape that uses wick materials and spray nozzles to improve the evaporation of water and increase freshwater output. Two solar distillers were built: one modified called a modified solar still (MSS) and a standard reference double slope solar still (RSS). A hybrid artificial intelligence model combining long short-term memory (LSTM) with the great wall construction algorithm (GWCA) was also created to predict saltwater temperature and freshwater production based on various factors like time and solar conditions. The results showed that the MSS produced 7.94 kg/m^2/day of freshwater, which is a significant 49.53% more than the RSS's 5.31 kg/m^2/day. The energy efficiency of the MSS was 57.40%, while the RSS was at 39.80%. Attia et al.[47] conducted a study to explore methods for increasing the volume of freshwater generated by a hemispheric solar distiller. To improve heat absorption and serve as an economical energy storage solution, spherical rock salt balls are introduced into the saline water basin. The findings indicated that the largest salt balls (2.0 cm) yield 6.77 kg/day.m^2 of freshwater, which is considerably higher than the 4.65 kg/day.m^2 produced by the reference distiller. Abdelgaied et al.[48] investigated the efficacy of a modified hemispherical solar still (MHSS) in comparison to a traditional hemispherical solar still (THSS). The modifications incorporated paraffin wax as PCM along with copper oxide nanoparticles. Three distinct scenarios of MHSS were evaluated: one featuring 0.3 wt% CuO in the water, another with a PCM container situated beneath the basin, and a third that integrated both modifications. Experiments carried out in El-Oued, Algeria, revealed that the application of CuO or pure PCM enhanced freshwater productivity by 60.41% and 29.17%, respectively. The most favorable outcomes were achieved through the simultaneous use of both PCM and CuO, which resulted in an 80.20% increase in productivity. This combination led to a 75% reduction in freshwater production costs when compared to THSS.

Based on the previous investigations that dealt with improving the effectiveness of water productivity and the performance of solar water distillers shows that most of the investigations are numerically and experimentally presented the outcomes of a typical solar water distiller system with fixed fins on the absorber plate. Moreover, the literature review related to water solar distillers with added phase change material (PCM) and porous medium is very limited. Most of the countries, for example, Iraq, spent large values of oil to generate electricity, and some of this electricity is employed to purify water. Therefore, Iraq spent a lot of money to cover this issue, although Iraq remains suffering from a shortage of providing enough electricity to customers.[49–57] To overcome this issue, the government in Iraq can use solar energy to reduce the financial expenses resulting from using oil to generate energy, for example, using solar water distiller systems to purify water. Such a model may be employed in locations that suffer from a lack of drinking water, and therefore, the well water can be connected to this model to provide water that is available for human use is available.[56–60] Based on the above, there is no study in the literature where the single-slope and single-basin solar water distiller with added porous structure (stones) and phase change material (PCM) is experimentally performed. Since the typical solar distiller systems cannot heat water to its highest heat capacity, this issue can be improved issue by adding PCM and a porous structure to the system. To have precise results, an experimental investigation is required.

Therefore, the current study objective is to experimentally perform the actions of adding PCM, extended surfaces, and porous structure (stones) above the basin plate on the effectiveness and water productivity of a single basin, one slope solar water distillation system. To explore the impacts of adding PCM and stones, the effectiveness of the new model and normal model is tested and compared under the same weather and operating conditions. The normal model is called (SD-F), whereas the new model that utilizes PCM and stones is called (MSD-FSP). Both models use rectangular fins that are fixed above the absorber plate. A paraffin wax is used as a PCM, where the PCM is filled inside tubes. The MSD-FSP model is tested with only adding PCM and PCM with stones. The concept of using PCM and stones above the absorber plate improves the heat exchange between thermal storage material and water and stores the heat throughout the day. As a result, it releases most of the heat from the absorber by heating water to its optimal heat capacity. This issue will act to raise the performance of the solar water distillation system. To present the effectiveness of MSD-FSP, the tests are performed in Mosul City/Iraq during November and December of 2023 for various water depths. The results of solar radiation, temperatures of basin water PCM, glass, water productivity, and effectiveness are presented with only adding PCM, PCM with stones, and without PCM and stones.

2 | METHODOLOGY

The present research was conducted at Northern Technical University located in Iraq/Mosul City during November and December of 2023. Over 4 days, the performance of the modified system is evaluated from 8 a.m. to 7 p.m. and compared with the normal system for an entire day. Since the efficacy of a normal solar water distiller system is limited due to the inability to fully desalinate water to its maximum capacity, to enhance the performance of such a system, incorporating stones and tubes filled with PCM above the basin surface can be a viable solution. To investigate this improvement, experiments were conducted on a single basin and single slope SD system with and without the addition of stones and tubes packed with PCM above the basin surface.

2.1 | Test-Rig components

Two systems are designed and constructed in this work to investigate the impact of incorporating stones and tubes filled with PCM on the system performances. Both systems have rectangular fins positioned above the basin. The absorber of the first model (normal model referred to as SD-F) has only rectangular fins, and the absorber of the second model (modified model referred to as MSD-FSP) incorporates fins, stones, and PCM. Figure 1 displays the schematic view of SD-F and MSD-FSP systems. The SD-F model is similar to the model built by.[10] The basins of the SD-F and MSD-FSP systems are made from galvanized iron sheets having 2 mm thickness. The distiller's body is insulated with 20 mm thick cork on five sides and then subsequently is housed within a wooden box to minimize heat losses to the surrounding environment. The thickness of the wooden box is 18 mm. The fins arranged in staggered form have dimensions of 80 mm (length), 40 mm (width) and 2 mm (thickness), with a space of 50 mm between each fin made from the galvanized iron sheet fixed above the absorber surface. Both the fins and basin liners are painted black to increase the amount of absorption of incident solar radiation. In the case of the MSD-FSP system, stones and PCM (paraffin wax filled inside tubes) are added above the basin. Table 1 displays the properties of PCM (paraffin wax) used in the tests.[52,53,56,57] Figure 2 shows the photograph of stones. It is important to note that the collectors of both systems have the same size and surface area. The inclined condensing cover for both systems is constructed using 6 mm thick glass, with an angle of 46° concerning the horizontal. A PVC tube collects the condensate water, which moves along the interior surface of the glass cover. The collected water condensate is subsequently measured in a jar. The tests are done based on the standard conditions of ASHRAE Anon.[61,62] To conduct an accurate comparison, the effectiveness and water productivity of SD-F and MSD-FSP systems were assessed in identical weather conditions to highlight the impact of using PCM and stones in the MSD-FSP system.

2.2 | Preparing of PCM

The total count of PCM tubes is 10, each having a diameter of 16 mm, and every tube contains 0.08 kg of paraffin wax as the phase change material (PCM). Taking into account the volume expansion of the PCM during its phase transition, each tube was filled with paraffin wax at a fill volume ratio of 84%. Subsequently, the ends of the tubes were sealed to avert any possible leakage of the PCM.

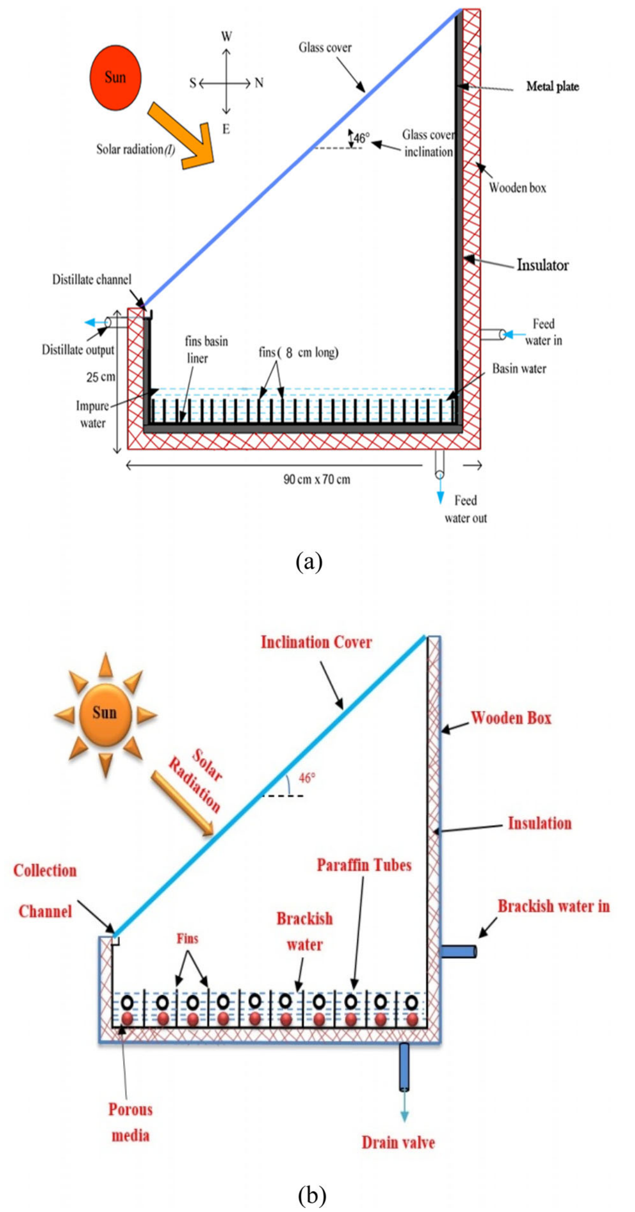

FIGURE 1 Schematic view of (a) normal model SD-F[10] and (b) modified model MSD-FSP.

2.3 | Experimental procedure

The experiments are conducted under two various water depths (30 and 50 mm). Before starting the tests, all the equipment is checked to ensure that there are no leaks at any joints. The real photo of the systems is presented in Figure 3. Throughout the experiments,

TABLE 1 Properties of paraffin wax.[52,53,56,57]

Properties	Value
Melting point	54°C – 57°C
Solid specific heat, Cp_S	2 kJ/kg.K
Liquid specific heat, Cp_L	2.15 kJ/kg.K
Solid thermal conductivity, K_S	0.22 W/m.K
Liquid thermal conductivity, K_L	0.24 W/m.K
Solid density, ρ_S	910 kg/m^3
Liquid density, ρ_L	790 kg/m^3
Fusion of Latent heat	170 kJ/kg
Expansion of volume	16%
Total mass of paraffin wax for 10 circular pipes	0.8 kg
Manufacturer source	Poth Hille & co Ltd Local market

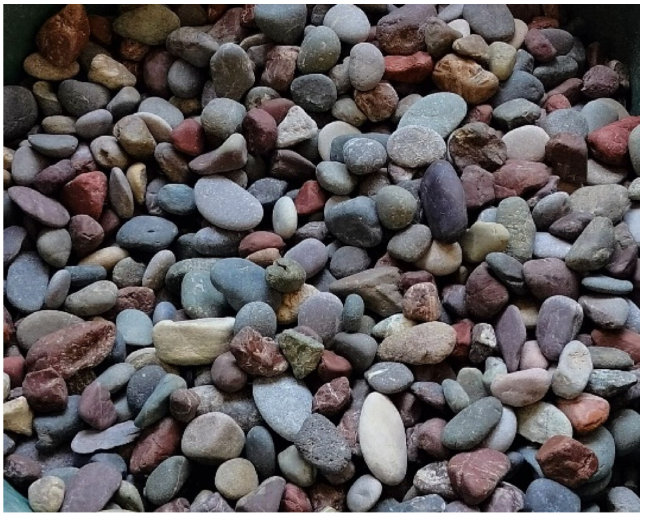

FIGURE 2 A photograph of stones used in the experiment.

measurements are taken for the solar radiation, as well as the temperatures of water, glass, vapor, and surrounding from 8 a.m. to 7 p.m. The solar irradiation is measured using a digital pyranometer (Seaward Solar Survey 100 Irradiance Meter) with an accuracy of ±0.85 W/m^2. Additionally, multi-channel thermocouples with an accuracy of ±0.65°C are utilized to read the temperatures. A measuring scale cylinder is employed to accurately determine the volume of condensate water.

3 | MODEL ANALYSIS

The system efficiency (η_{dms}) and water output (M'_{dms}) are computed as[52,53,63]:

$$M'_{dms} = \sum M_{ms} \tag{1}$$

$$\eta_{dms} = \frac{M'_{dms}\ L_{ev}}{\sum I * 3600 * A_b}\ (I \text{ is measured every 15mins}) \tag{2}$$

where I, L_{ev}, and M_{ms} illustrate the total solar intensity, evaporation latent heat and the total distillate water production over a period of 10 h, respectively. The evaporation latent heat is calculated as follows Tiwari and Tiwari:[64]

For Tv < 70°C,

$$L_{ev} = 2.4935 \times 10^6 \left(1 - 9.4779 \times 10^{-4} \times Tv + 1.3132 \times 10^{-7} \times Tv^2 - 4.7974 \times 10^{-9} \times Tv^3\right) \tag{3}$$

For Tv > 70°C,

$$L_{ev} = 3.1615 \times 10^6 \left(1 - 7.616 \times 10^{-4} \times Tv\right) \tag{4}$$

4 | UNCERTAINTY ANALYSIS

The uncertainty analysis for the current investigation is involved in analyzing the errors. The effectiveness η_{dms} is presented in terms of known quantities of water productivity, latent heat of evaporation, and solar radiation $\eta_{dms} = f(M'_{dms}, I, L_{ev})$ Bonnichsen.[58,60,65] The uncertainties of electrical and thermal efficiencies $\omega_{\eta_{el}}$ and $\omega_{\eta_{th}}$ are obtained as:

$$\omega_{\eta_{dms}} = \left\{ \left(\frac{\partial \eta_{dms}}{\partial \acute{m}} \omega_{\acute{m}}\right)^2 + \left(\frac{\partial \eta_{th}}{\partial M'_{dms}} \omega_{M'_{dms}}\right)^2 + \left(\frac{\partial \eta_{th}}{\partial I} \omega_I\right)^2 \right\}^{0.5} \tag{5}$$

The largest uncertainty values of η_{dms} were obtained from Equations (5) is obtained equal to 4%.

5 | RESULTS AND REMARKING DISCUSSION

This work evaluates the impact of incorporating PCM and stones on the absorber surface of a modified solar water distiller collector (MSD-FSP) compared to a standard solar distiller collector (SD-F). Both collectors share identical dimensions and surface areas. Integrating PCM and stones aims to enhance heat exchange between the basin plate and water while storing thermal energy for delayed release during low solar radiation periods. This approach resulted in higher water temperatures and increased productivity of the distiller system. Experiments were conducted using two different water depths, 30 and 50 mm, during the months of November and December 2023 to assess the impacts of varying solar irradiance levels on system performance.

5.1 | Variations of incident solar radiation

The hourly variations in solar radiation (I) for both configurations were recorded over multiple test days, and the data is illustrated in Figure 4. Among all the test days, November 7 exhibited the highest solar irradiance, reaching a peak value of 954 W/m^2 between 11 a.-m. and 12 p.m. Following this peak, a steady decline in solar irradiance was observed beyond noon for all experimental days. This trend suggests a direct correlation between solar energy availability and the thermal performance of the system. Furthermore, the results emphasize that the energy required for water evaporation is significantly influenced by the solar irradiance intensity received by the collector, as higher radiation levels contribute to increased thermal energy absorption, thereby enhancing the evaporation process. These

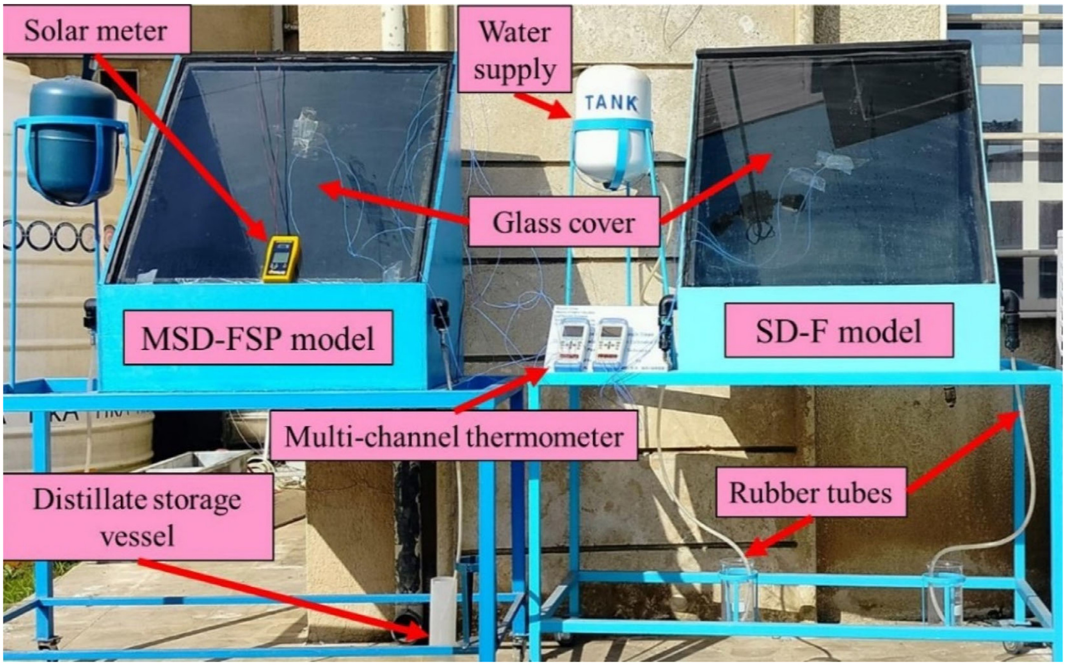

FIGURE 3 A real photo of (a) normal model SD-F (right side) and (b) modified model MSD-FSP (left side).

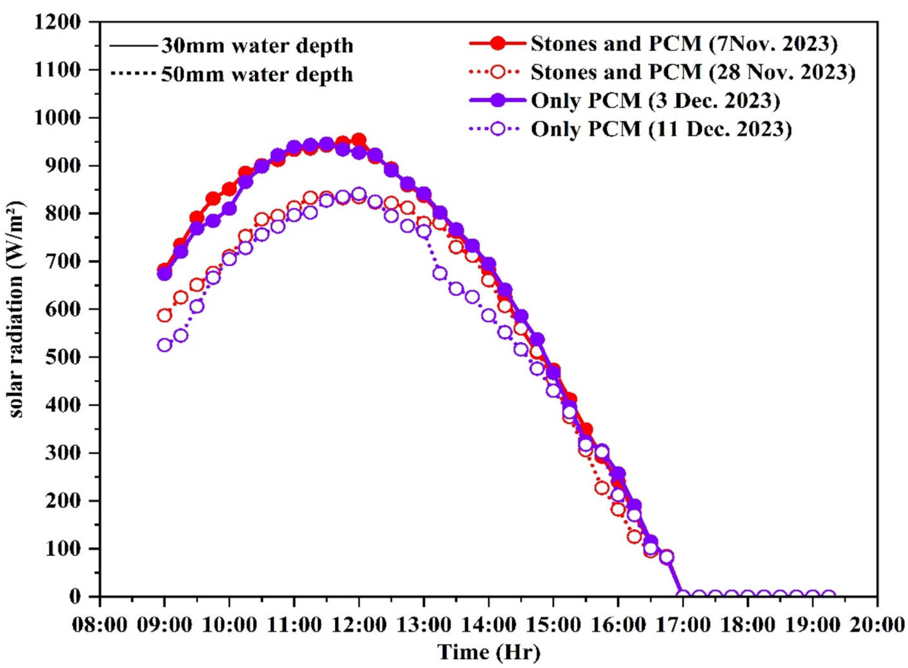

FIGURE 4 Fluctuations in solar radiation intensity across various days and water depths.

findings reinforce the crucial role of solar intensity in governing the overall efficacy of the system.

5.2 | Variations of water temperature

Figure 5 presents the temporal variations in water temperature (*Tw*) for water depths of 30 and 50 mm in SD-F and MSD-FSP models, with the data derived from Figure 4. The findings demonstrate that water depth plays a crucial role in governing Tw, as shallower depths facilitate greater heat absorption due to enhanced heat exchange, leading to higher temperatures. Across both configurations, Tw reaches its peak between 1 and 3 p.m. before progressively declining by 7 p.m., a trend influenced by the interplay of solar intensity, ambient temperature fluctuations, and water depth. Notably, the integration of stones in the MSD-FSP model significantly amplifies heat transfer by increasing the available surface

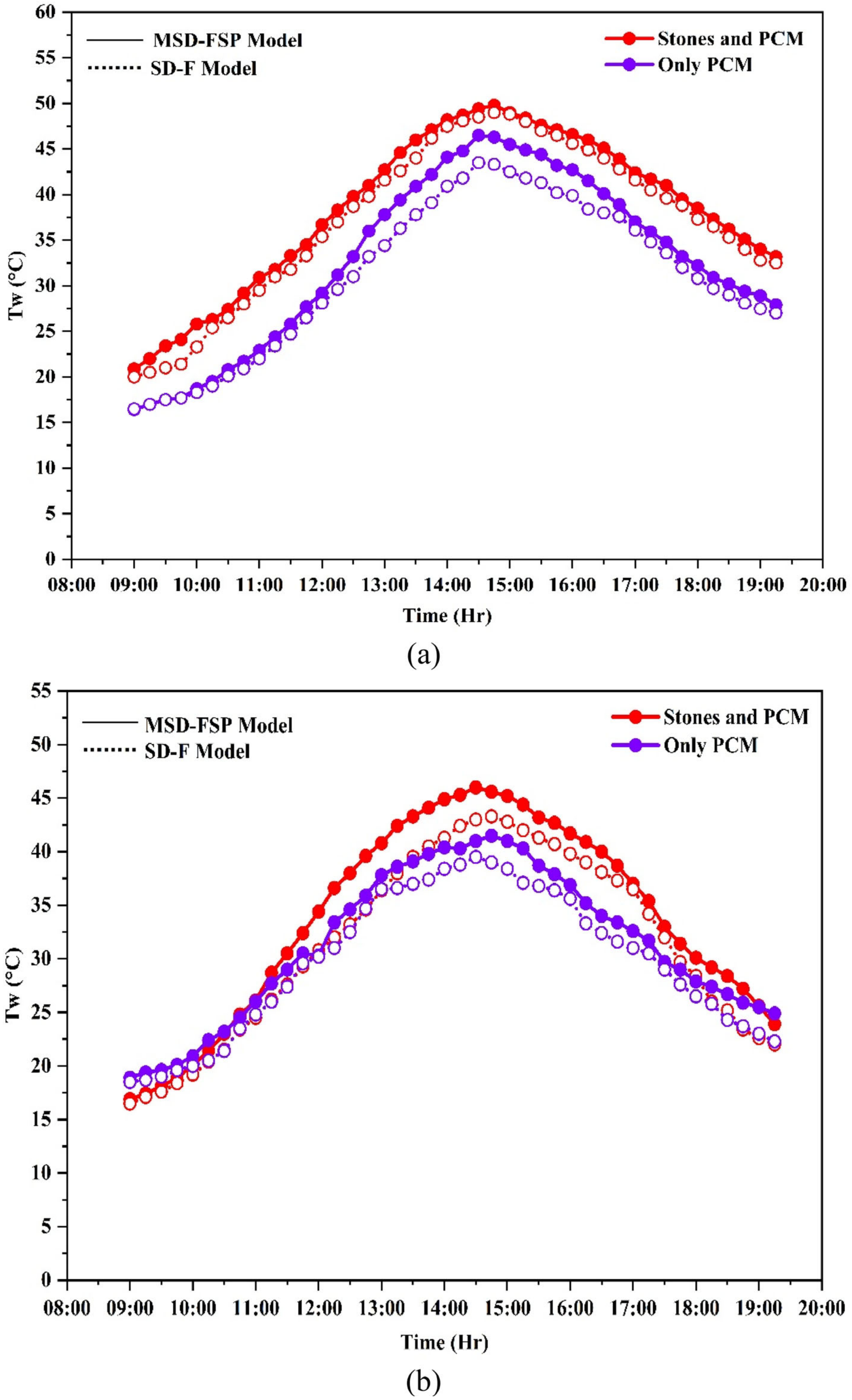

FIGURE 5 Fluctuations in basin water temperature analyzed at depth (a) 30 mm and (b) 50 mm.

area for thermal exchange, thereby raising Tw and accelerating water evaporation. Furthermore, the incorporation of PCM enables the system to store thermal energy during daylight hours and gradually release it after sunset, extending heat availability beyond peak solar hours. Comparative analysis reveals that the MSD-FSP model consistently outperforms the SD-F model in achieving higher Tw, with maximum recorded temperatures of 49.8°C for 30 mm and 46.3°C for 50 mm, compared to 49.1°C and 43.6°C in the SD-F system. These results underscore the superior thermal efficiency of the MSD-FSP configuration, demonstrating its effectiveness in optimizing heat retention and evaporation processes.

5.3 | Variations of PCM and stone temperatures

Figure 6 illustrates the temperature dynamics of phase change materials (PCM) and stones within the MSD-FSP model under various

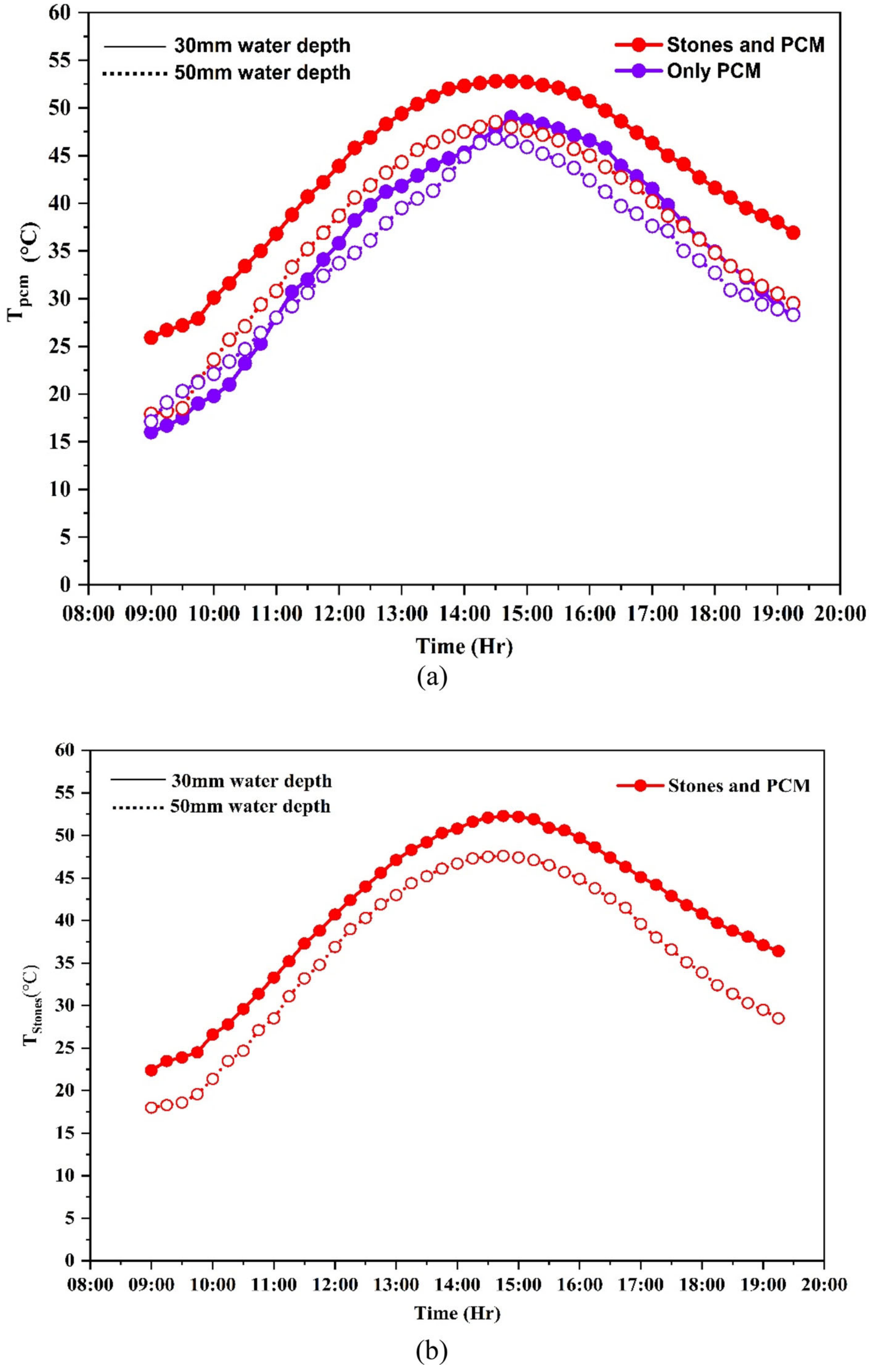

FIGURE 6 Temperature behaviors of (a) PCM (b) stones.

depths of water. The data reveal that the combination of stones and PCM leads to a notable increase in PCM temperature, with maximum recorded values of 52.8°C at a 30 mm depth and 48.3°C at a 50 mm depth. This trend underscores the role of stones in augmenting heat transfer, allowing PCM to achieve higher temperatures compared to when it is used in isolation. The fundamental function of PCM in the system is to absorb and store thermal energy during peak solar hours and subsequently release it during periods of reduced or no sunlight, thereby sustaining thermal energy availability and enhancing water evaporation efficiency. Additionally, Figure 6b depicts the thermal behavior of the stones, which reach peak temperatures of 52.6°C at 30 mm and 47.1°C at 50 mm, directly correlating with the highest recorded solar irradiance of 954 W/m^2. Acting as sensible heat storage materials (SHSM), the stones capture and retain solar energy throughout the day, gradually releasing it after sunset. This prolonged heat contribution helps maintain elevated water temperatures, improving the overall thermal performance and ultimately enhancing freshwater productivity.

5.4 | Variations of vapor water temperature

Figure 7 illustrates the vapor water temperature dynamics for the SD-F and MSD-FSP models, a critical parameter that directly impacts the evaporation and condensation processes in saline water treatment, ultimately influencing system productivity and efficiency. The

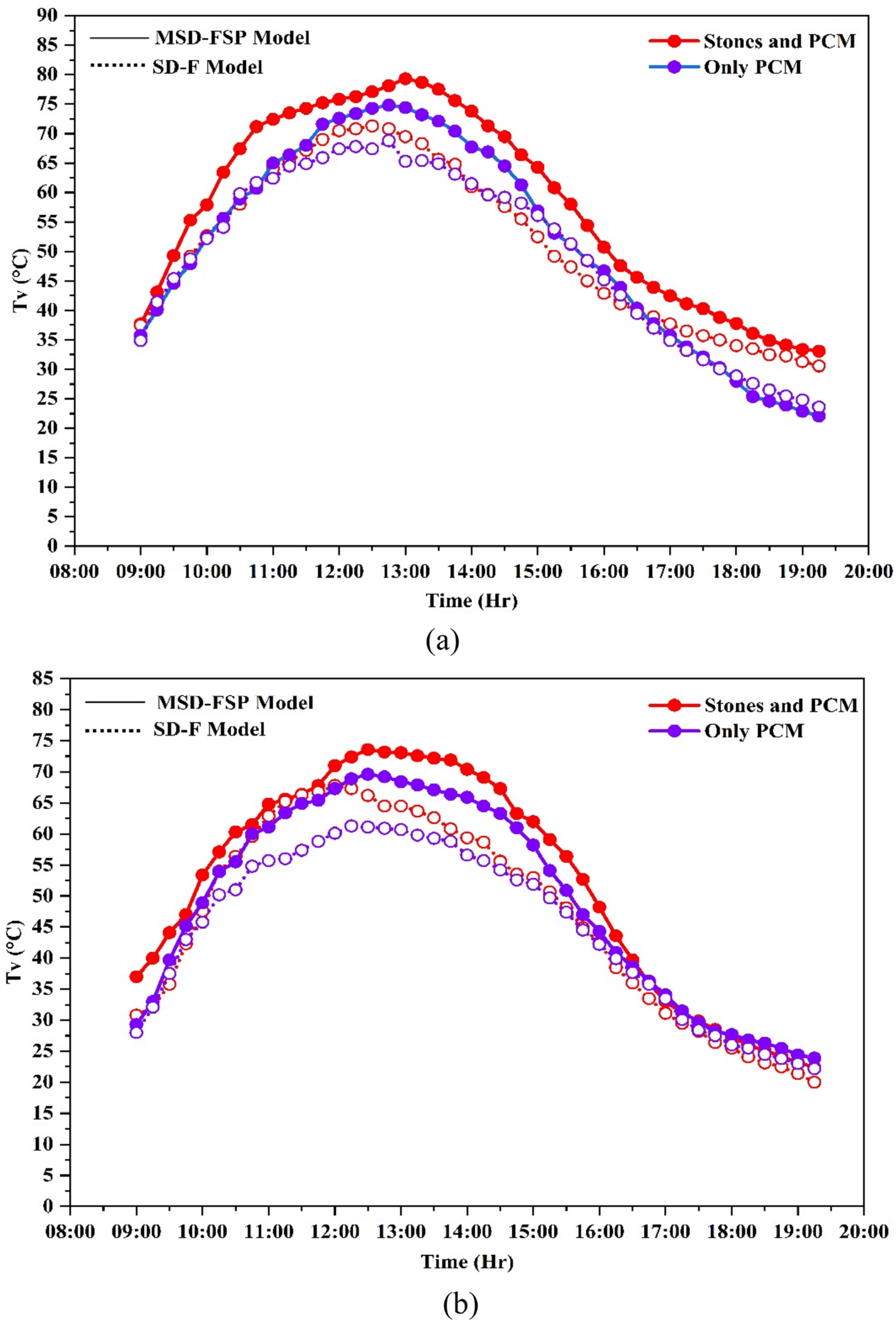

FIGURE 7 Water vapor temperature behavior for SD-F and MSD-FSP models under various water depths (a) 30 mm and (b) 50 mm.

vapor temperature is governed by multiple interacting factors, including solar radiation intensity, the thermal properties of stones and PCM, water basin temperature, the absorptivity of the basin's plate, and water depth. The outcomes indicate that the MSD-FSP model, which integrates both stones and PCM, consistently achieves the highest peak vapor water temperature compared to the SD-F model. This improvement is attributed to increasing the heat exchange surface area provided by stones and PCM, which facilitates more efficient thermal transfer between the water and absorber plate. Thus, the evaporation rate is significantly improved, leading to superior overall system performance and increased freshwater yield.

5.5 | Variations of absorber plate temperature

This study investigates the variations in absorber plate temperature (Tp) within two solar distillation models, MSD-FSP and SD-F, at water depths of 30 and 50 mm, emphasizing its critical role in evaporation dynamics and distilled water yield. The results indicate that for water depth 30 mm, the MSD-FSP model, which integrates stones and PCM, achieves a peak Tp of 64°C, surpassing the SD-F model's maximum of 61.1°C. Similarly, at a 50 mm depth, the MSD-FSP model reaches 58.9°C, exceeding the 56.3°C recorded for the SD-F model. These findings highlight the direct relationship between higher Tp and improved thermal energy transfer to the water, accelerating evaporation and ultimately increasing freshwater production efficiency, as presented in Figure 8.

5.6 | Evaluation of water productivity

Figure 9 displays the cumulative water productivity and efficiency for SD-F and MSD-FSP models under different water depths for stones with PCM and for only PCM. The maximum enhancement in the

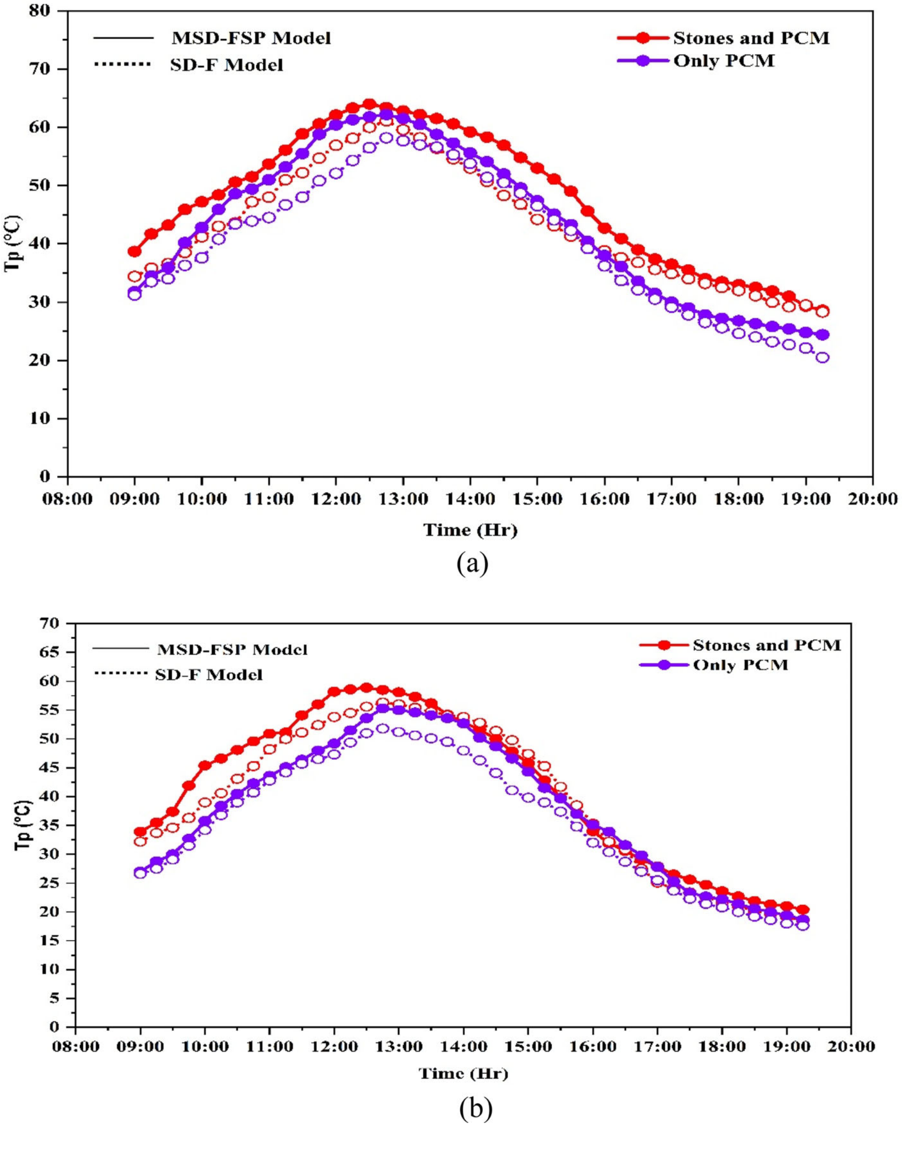

FIGURE 8 Behavior of absorber plate temperature for water depth (a) 30 mm and (b) 50 mm.

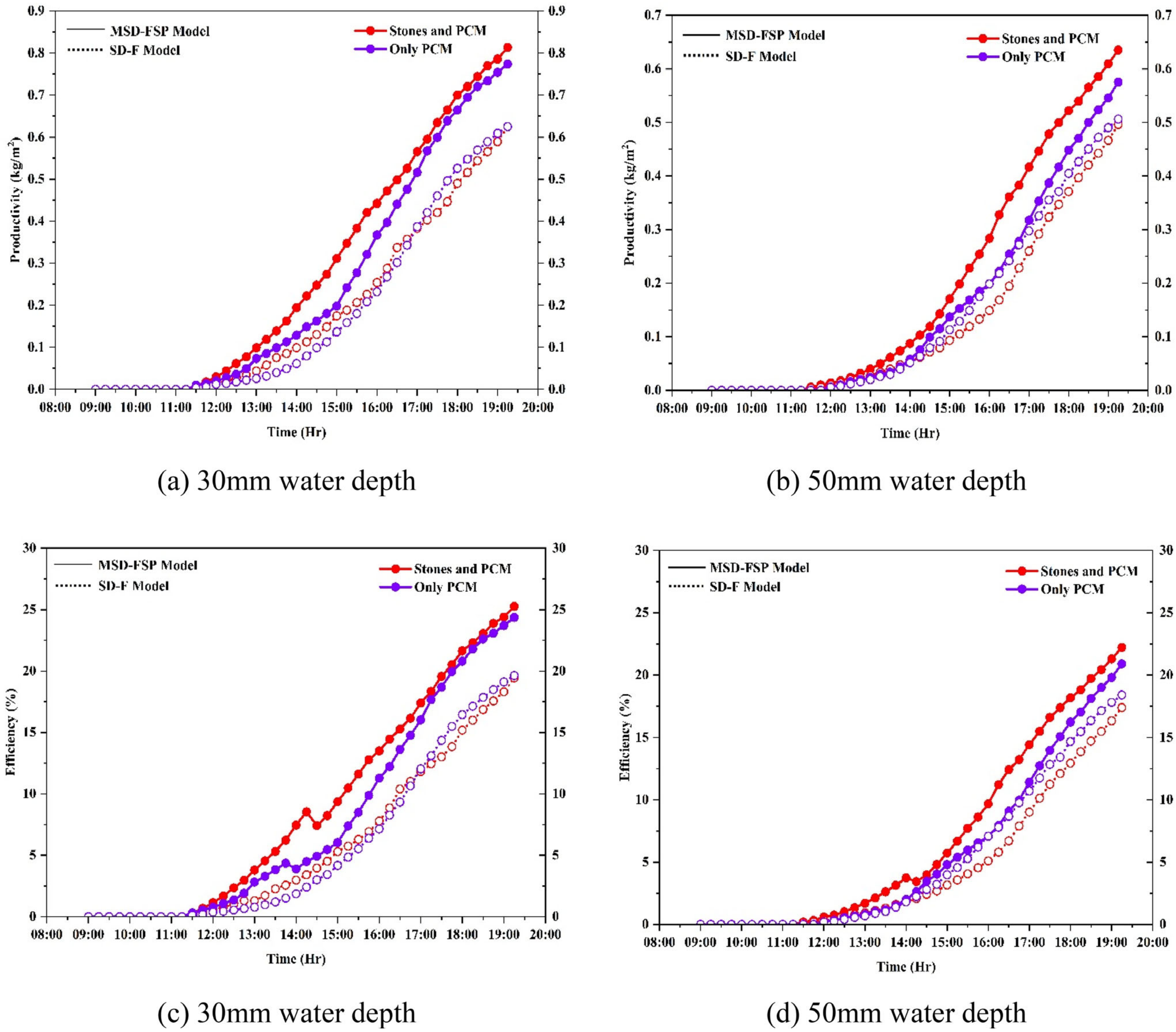

FIGURE 9 Variations of water productivity and efficiency analyzed for MSD-FSP and SD-F models. (a) productivity at 30 mm water depth (b) productivity at 50 mm water depth (c) efficiency at 30 mm water depth (d) efficiency at 50 mm water depth.

productivity and efficiency of the MSD-FSP model as compared to the SD-F model is obtained as follows (Yadav and Prakash[66]):

$$\text{enhancement in } M'_{dms} = \left| \frac{M'_{dms\,MSD-FSP} - M'_{dms\,SD-F}}{M'_{dms\,SD-F}} \right| \times 100 \qquad (6)$$

$$\text{enhancement in } \eta_{dms} = \left| \frac{\eta_{dms\,MSD-FSP} - \eta_{dms\,SD-F}}{\eta_{dms\,SD-F}} \right| \times 100 \qquad (7)$$

The results illustrated in Figure 9a,b demonstrate a significant improvement in water productivity for the MSD-FSP model compared to the SD-F model, with an increase of 35% at a water depth of 30 mm and 28% at 50 mm. The MSD-FSP model, incorporating stones and phase change material (PCM), achieves a peak water productivity of 0.81 kg/m^2 at a 30 mm depth, whereas the SD-F model reaches a maximum of 0.60 kg/m^2 under the same conditions. Furthermore, Figure 9c,d reveal a substantial enhancement in the efficiency of the MSD-FSP model over the SD-F model, with the highest recorded efficiency improvements of 31% at a 30 mm depth and 27% at 50 mm. This performance boost is primarily attributed to the integration of stones and PCM above the basin, which enhances the accessible surface area for heat transfer and promotes effective thermal energy retention. The stored heat is gradually released during evening hours, ensuring prolonged thermal energy availability, thereby sustaining water productivity and efficiency beyond peak sunlight hours. These findings highlight the superior capability of the MSD-FSP model in optimizing solar energy utilization and maximizing freshwater production.

5.7 | Evaluation of total dissolved solid

Figure 10 shows the reading of Total dissolved solid (TSD) for sea water before and after the distillation process; the findings indicated that the quality of water is excellent for drinking water used according to Herschy[67] based on WHO guidelines.

5.8 | Economic evaluation

In the present, the analysis of the distilled water system for both SD-F and MSD-FSP models is conducted based on the following assumptions:

- The cost of materials (galvanized iron, insulation cork, glass, wooden structure) is the same for both systems.
- The additional components in the MSD-FSP system are 10 USD for PCM-filled tubes (0.8 kg of paraffin wax total) and local natural stones (∼2 kg) which represent low-cost and readily available options in local markets in Iraq.
- The lifetime of both systems is assumed to be 5 years and operating 300 days/year.
- The cost of paraffin wax is ∼10 USD/kg, making the total PCM cost ≈ 8 USD

The results of water productivity showed that the MSD-FSP model produced 0.81 kg/m^2/day and SD-F is 0.60 kg/m^2/day. Therefore, the water productivity over 5 years for the MSD-FSP model yields ≈ 1215 kg/m^2 whereas for the SD-F model yields ≈ 900 kg/m^2. The cost per liter (USD/liter) is presented in Table 2.

Despite the small additional investment in the initial cost of MSD-FSP, it can be displayed from Table 2 that the cost per liter of distilled water is reduced by nearly 30% when using MSD-FSP model as compared to SD-F model. The cost per liter of freshwater produced by MSD-FSP is estimated to be lower in the long run due to its enhanced productivity and the passive nature of the system, which requires no electricity or additional energy sources. This confirms that the use of PCM and stones not only improving the system performance (water productivity) but also improving the economic feasibility, especially in the regions with high solar potential and limited access to clean water.

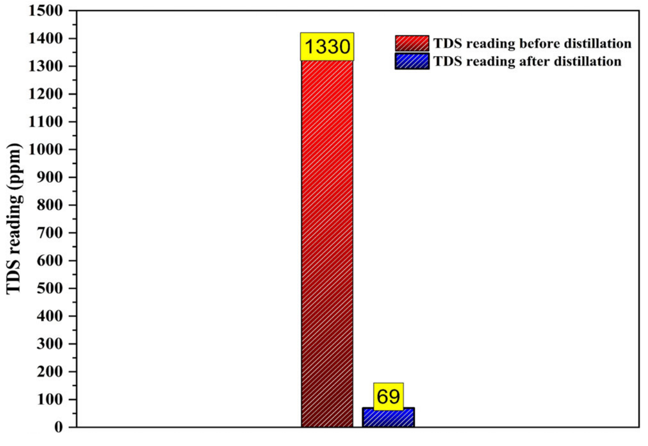

FIGURE 10 Reading of total dissolved solid (TSD).

6 | NOVELTY AND STATEMENT OF INDUSTRIAL RELEVANCE

Based on the previous works dealing with improving the effectiveness of solar water distillers, it is apparent that most of the works presented solutions for the typical solar water distiller with fixed fins on the absorber plate, where those works are experimentally and numerically performed. Furthermore, the literature review explores that the works related to water solar distillers integrated with porous structures and PCM are rare. As may be known, Iraq is one of the countries that continuously spends large amounts of electricity generated from burning oil, and some of this electricity is employed to purify water; hence, Iraq spends huge amounts of money on this issue, although Iraq remains suffering from a shortage of providing enough electricity to consumers;[56,57] Omar and Alomar.[49–55] However, the government in Iraq can use solar energy to reduce the financial expenses resulting from using oil to generate energy, for example, using solar water distiller systems to purify water in the locations that suffer from a lack of drinking water.[56–60] Based on the foregoing discussions, there is no available study conducted to explore the performance of single-slope and single-basin solar water distillers with integrated stones (as porous structure) and PCM inside tubes. This integration aims to achieve more heat gain and increase the surface of heat exchange. Since the typical solar distiller systems cannot heat water to its highest heat capacity, this issue can be improved issue by adding PCM and a porous structure to the system. To have precise results, an experimental investigation is required.

7 | LIMITATION OF INVESTIGATION

This paper highlights the key factors that affect the performance of a single-basin single-slope solar water still system and improvements that enhance its water productivity by addressing various aspects, for example, heat storage materials (PCM and porous structure), water depth, and cost-effectiveness over extended periods. Also, is presented two models and the analysis methods are presented for the purpose of comparison. Additionally, while significant improvements are discussed, further studies are needed to validate the practical implementation of these enhancements in diverse conditions. However, this work does not present the impacts of, for example, thickness and glass cover, inclination angle, basin dimensions, prevailing environmental conditions, and long-term performance, which may limit the broader applicability of the findings. To help researchers gain a better understanding of this problem, the present study is necessary to demonstrate the gap in this matter.

TABLE 2 Cost per liter (USD/liter) for tested models.

Configuration	Added cost (USD)	5-year productivity (kg)	Approx. cost/Liter
SD-F	0	900	Baseline
MSD-FSP	+8	1215	0.0065 USD/liter

8 | CONCLUSIONS AND FUTURE INVESTIGATIONS

Based on the current findings, the main conclusions were drawn:

1. **Enhanced Productivity and Efficiency of MSD-FSP Model**: The MSD-FSP model demonstrated superior performance compared to the SD-F model, with a 35% improvement in daily yield and a 31% increase in efficacy at a water depth of 30 mm. For a water depth of 50 mm, the productivity and efficiency of the MSD-FSP model were 28% and 27% higher, respectively, than those of the SD-F model. These results highlight the significant impact of incorporating stones and PCM in enhancing the distiller's performance.
2. **Higher Maximum Water Temperature**: The maximum water temperature recorded in the MSD-FSP model was 49.8°C at a depth of 30 mm, which is slightly higher than the 49.1°C achieved by the SD-F model under similar conditions. This temperature difference underscores the effectiveness of heat retention and transfer facilitated by stones and PCM in the basin.
3. **Optimal Water Productivity with Reduced Water Depth**: The highest water productivity achieved by the MSD-FSP model was 0.81 kg/m^2 at a depth of 30 mm. This finding demonstrates that maintaining a shallower water depth optimizes the evaporation process and, consequently, the distiller's productivity.
4. **Key Factors Influencing Solar Distiller Performance**: The system performance is significantly influenced by several parameters, including the thickness and glass cover inclination angle, the basin dimensions, prevailing environmental conditions, and the solar incident intensity. These factors directly affect heat absorption, retention, and overall distillation efficiency.
5. **Impact of Stones and PCM on Thermal Performance**: The addition of stones and PCM substantially enhances the heat exchange within the basin. Stones act as thermal storage elements, improving the evaporation rate, while PCM facilitates latent heat storage. The combined effect of these materials improves the heat transfer rate and overall performance of the distiller.
6. **Role of PCM in Energy Storage and Release**: PCM serves as an effective latent heat storage material, capturing excess solar energy during peak sunlight hours and releasing it during periods of low or no solar radiation. This functionality ensures that water in the basin remains heated even after sunset, resulting in a sustained improvement in productivity.
7. **Inverse Relationship Between Water Depth and Productivity**: The efficiency of the solar distiller decreases as the water depth in the basin is increased. Shallower water depths allow for quicker heating, enhanced evaporation rates, and subsequently higher distillation output.
8. **Water Quality:** The solar distiller showed its ability to improve water quality, as the readings of the TDS meter showed a significant decrease in the level of dissolved salts in the water, which corresponds to the standards of the World Health Organization.

In summary, the study highlights the remarkable advantages of integrating stones and PCM in solar distillers. These enhancements provide a feasible solution for improving water productivity and thermal efficiency, making the MSD-FSP model a promising design for regions with high solar potential and water scarcity challenges.

To further improve this work, the following future investigations are suggested:

1. Conducting a new experimental investigation on the performance of double-slopes MSD-FSP model. This work is required to compare the current findings and to explore the impact of the number of inclination.
2. Prospective work shall involve the performance of a hybrid solar distiller with auxiliary heating for night operation.
3. Conducting a theoretical investigation on the performance of the MSD-FSP model under similar operating conditions. The theoretical results are required to verify the experimental results.
4. Examining the impacts of utilizing different PCM (e.g., nano-enhanced wax) and porous structure (e.g., various permeability and porosity of stones) on the performance of the MSD-FSP model.

NOMENCLATURE

A_b	Basin area, m^2
M_{mx}	Hourly distillate productivity, ml
M'_{dms}	Daily distillate productivity, kg/m^2
L_{ev}	Evaporation Latent heat, J/kg
I	Intensity of solar radiation, W/m^2
η_{dms}	Efficiency of the Solar Still (%)
T_W	Basin's water temperature, °C
T_v	Vapor temperature, °C
T_{pcm}	Temperature of phase change materials, °C
$T_{st.}$	Stones temperatures, °C
T_p	Absorber plate temperature, °C
C_p	Specific heat, KJ/Kg.K
K	Thermal conductivity, W/m.K
P	Density, Kg/m^3

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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