
Research article

Augmenting solar still productivity through phase-change materials and nano-enhanced PCM composites

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Abstract: Low productivity remains a key limitation of conventional solar stills for desalination. In this study, we evaluated the performance of a solar still integrated with copper rods filled with nano-enhanced phase change material (NPCM), benchmarked against three configurations: a conventional still, a still with empty copper rods, and a still using unmodified phase change material (PCM). Four single-slope solar stills were fabricated and tested simultaneously under identical ambient conditions. Distillate yield, temperature profiles, and thermal efficiency were recorded during daytime (9:00–17:00) and nighttime operation to assess the influence of dispersed nanoparticles on heat storage and release behavior. The NPCM still achieved a distillate yield of 4.27 kg/m²·day, compared with 1.98 kg/m²·day for the conventional still. The improved thermal conductivity and heat retention of the nano-PCM matrix resulted in a 19.4% higher nocturnal yield (1.49 kg/m²·day) relative to the PCM still (1.28 kg/m²·day). Peak rod temperature reached 86 °C for the NPCM configuration, versus 79 °C (PCM) and 68 °C (empty rod). Thermal efficiency increased from 47.20% (conventional) to 70.15% (NPCM), representing a 65% gain in productivity and a 48.62% improvement in efficiency. These findings confirm that nanoparticle dispersion in PCM enhances heat storage capacity, thermal distribution, and freshwater yield in solar stills. The NPCM-integrated design offers a promising route toward higher-efficiency, sustainable solar desalination for arid and coastal regions.

Keywords: solar still; phase change material (PCM); nano phase change material (NPCM); thermal energy storage; desalination; freshwater productivity; energy efficiency

1. Introduction

The global scarcity of freshwater has intensified in decades due to factors such as population growth, industrialization, and declining rainfall patterns. This issue is particularly critical in developing regions, where the availability of affordable water purification technologies remains limited. Among the potential solutions, solar desalination offers a sustainable and low-cost alternative, with the solar still being one of the simplest and most widely investigated devices. Solar stills, operating on the simple evaporation–condensation cycle, provide a low-cost and sustainable approach to desalination [1–3]. Solar stills are broadly classified into passive and active systems. In passive designs, the basin water is heated solely by direct solar radiation without external assistance such as electrical heaters or preheated water. Despite their simplicity, several modifications, such as optimizing basin geometry, saline water depth, orientation, and thermal insulation, have been proposed to enhance their thermal efficiency [4–7]. Panchal et al. [8] experimentally investigated three solar still configurations: a conventional still, a still with vertical fins, and a still with inclined fins. The reported daily distillate yields were 1.940, 2.440, and 2.540 L·m⁻², respectively, demonstrating the performance enhancement achieved through fin integration. To improve condensation, Rahbar et al. [9] designed a single-basin double-slope solar still in which one glass surface was exposed to sunlight while the other remained shaded, thereby lowering cover temperature and enhancing yield [10]. Alternative designs, such as tubular solar stills, have also been investigated, showing good agreement between experimental and theoretical results [11]. Furthermore, stepped solar stills, where the absorber is arranged in a staircase form, have demonstrated improved heat and mass transfer, leading to higher productivity [12]. To enhance solar still efficiency, many researchers have integrated phase change materials (PCMs) to exploit latent heat storage. PCMs absorb thermal energy during phase transitions, such as solid–liquid or liquid–gas, without significant temperature rise, storing heat in the form of latent energy. Upon cooling, the stored heat is released as the material reverts to its original phase. The heat storage and release capacity primarily depend on the mass and thermal properties of the PCM. The selection of a phase change material (PCM) requires consideration of properties such as melting point, density, thermal stability, and durability. Choice of PCM depends on the specific application, including the operating temperature range, required energy storage capacity, and material lifespan. High-melting-point PCMs, such as paraffin wax (PW), fatty acids, and salt hydrates, are widely used due to their ability to store and release significant latent heat over a narrow temperature range. PW, with a melting range of 40–90 °C, is particularly suitable for heating and electrical applications [13–15]. Several studies have demonstrated the effectiveness of PCMs in enhancing solar still performance. Kabeel and Abdelgaied [16] experimentally showed that incorporating paraffin wax as a PCM increased daily yield by 51–86% compared to a conventional still. Gnanavel et al. [17] conducted numerical simulations using paraffin C-18 and trimethylolethane as PCMs, reporting improved productivity in PCM-integrated stills. Vigneswaran et al. [18] examined a single-slope solar still with two types of paraffin-based PCMs, comparing three configurations: without PCM, with one PCM, and with two PCMs, and corresponding energy efficiencies were 38.72%, 42%, and 46%, respectively, highlighting the cumulative benefits of multi-PCM integration.

The application of nanotechnology has further enhanced PCM performance. Incorporating nanoparticles, such as graphene, carbon nanotubes, or metal oxides, into the PCM matrix increases thermal conductivity due to their high surface area-to-volume ratio, improving heat transfer and overall thermal energy storage efficiency [19]. Nanoparticles not only increase PCM thermal conductivity but also accelerate melting/solidification, reducing charging/discharging time and enhancing overall exergy efficiency. Such nano-enhanced PCMs (NEPCMs) represent a promising approach for overcoming the inherent limitations of conventional PCMs and extending solar still productivity beyond daylight hours. For example, the use of a high-thermal-conductivity graphite plate with paraffin wax significantly boosted solar still productivity, with a 62% improvement during daytime and a 235% increase at night [20]. Manoj Kumar et al. [21] demonstrated that mixing 0.5% silica with paraffin to form a nano-PCM increased solar still productivity by 67.04%, compared to a 51.22% increase using PCM alone. Sharshir et al. [22] reported that the addition of graphite nanoparticles in solar stills, when combined with PCM and glass film cooling, improved productivity by up to 73.8% compared to a conventional design. Similarly, Thalib et al. [23] compared conventional tubular solar stills with PCM and NPCM (paraffin wax + graphene nanoparticles) and observed daily distillate yields of 4.3 kg, 6.0 kg, and 7.9 kg, respectively, corresponding to energy efficiencies of 31%, 46%, and 59%. Recent techno-economic assessments further confirm these gains; for instance, Kushwah et al. [24] showed that a solar still modified with ZnO-NPCM achieved 113% higher yield and 51% thermal efficiency, while reducing the cost of freshwater production from \$0.030 to \$0.023 per liter. Hybrid nano-PCM systems have also been explored; Padmanaban et al. [25] integrated TiO₂ and graphene nanoplatelets with paraffin PCM and achieved nearly 69% higher productivity compared to a conventional still. Numerical investigations by Saeed et al. [26] highlighted that adding 3 vol.% Al₂O₃ nanoparticles to PCM could further improve productivity by about 20% relative to PCM-only systems. Similar trends were observed in experimental studies with Al₂O₃ and graphene oxide composites, which consistently demonstrated higher freshwater yields and extended operating hours [27,28].

Studies have shown that incorporating phase change materials (PCMs) and nano-enhanced PCMs (NPCMs) can improve the productivity of solar stills. However, much of the available literature has focused on commonly used oxide nanoparticles such as Al₂O₃ and SiO₂, as well as selected carbon-based materials. These investigations largely report short-term productivity enhancements, while comparatively fewer researchers examine detailed thermal behavior, night-time heat release, and overall system performance under consistent experimental conditions. As a result, the potential role of developed two-dimensional nanomaterials in PCM-assisted solar stills has not been extensively examined.

MXene nanoparticles were considered in this study because of their layered structure, well reported thermal conductivity range and its photothermal absorption properties, which arise from its two-dimensional structure and surface terminations. In comparison with conventional oxide nanoparticles, MXenes may offer improved interfacial heat transfer with PCMs at relatively low concentrations; however, their practical influence in solar still systems remains insufficiently documented. Here, we do not seek to establish superiority over nanoparticles but rather to explore their applicability within a PCM-based solar still framework.

Accordingly, we contribute by presenting an experimental comparison of conventional, empty rod, PCM, and MXene-based NPCM solar stills operated under the same climatic conditions. By jointly examining daytime productivity, night-time distillation behavior, thermal response of the storage medium, and overall energy efficiency, the work provides additional experimental data that complement NPCM studies and may assist in guiding future material selection and system optimization efforts.

2. System description

The experimental investigation was carried out using four single-slope solar stills of identical geometry, fabricated and operated simultaneously to ensure that all units were exposed to the same climatic conditions throughout the testing period. The four stills differed only in their internal heat-storage configuration and were designated as Still-I (conventional still, without rods), Still-II (fitted with empty copper rods), Still-III (fitted with copper rods filled with phase change material, PCM), and Still-IV (fitted with copper rods filled with nano-enhanced phase change material, NPCM). This arrangement allowed a direct, controlled comparison of the effect of rod-based thermal storage, and specifically the effect of nanoparticle dispersion within the PCM, on still performance. Each solar still was constructed as a rectangular basin measuring 1000 mm in length and 1550 mm in width, with a sloped profile giving a back-wall height of 625 mm and a front-wall height of 115 mm. The basin was fabricated from galvanized iron sheet, chosen for its corrosion resistance and durability under prolonged exposure to saline water and outdoor conditions. The interior basin surface was coated with black paint to maximize the absorption of incident solar radiation and enhance the conversion of solar energy into heat within the basin water.

To minimize conductive and convective heat losses to the surroundings, the basin was insulated on its outer sides and base using a combination of glass wool and 3 mm-thick thermocol sheets, both of which offer low thermal conductivity and help retain heat within the system during operation. The top of each still was covered with a transparent glass sheet of 8 mm thickness, inclined at an angle of 28° to the horizontal. This tilt angle was deliberately selected to correspond closely with the geographical latitude of the test site (28°N , Aligarh, Uttar Pradesh, India), a standard design practice that ensures near-optimal incidence of solar radiation on the glass cover across different seasons of the year. The inclined glass cover serves a dual function: It enables solar radiation to enter and heat the basin water, and it provides a sloped condensing surface along which water vapor, upon condensation, trickles down under gravity into a collection channel and is subsequently guided into a distillate collection container. At the heart of the thermal storage enhancement was a set of ten copper rods, each 18 mm in diameter, installed within the basin of each still (except Still-I) and fully immersed in the saline water at equally spaced positions. Copper was selected as the rod material owing to its high thermal conductivity, which facilitates rapid heat absorption during periods of high solar insolation and efficient heat release during periods of low or no solar input. The equidistant placement of the rods across the basin was intended to promote uniform heat distribution throughout the water mass, avoid localized hot or cold zones, and increase the effective surface area available for heat exchange between the rods and the surrounding water. This, in turn, was expected to enhance the rate of evaporation and improve the overall freshwater yield.

The four experimental configurations were tested under a constant basin water depth of 10 mm to maintain uniformity in thermal mass across all cases. In Still-I, no rods were used, representing the baseline conventional design. In Still-II, the ten copper rods were left empty (hollow), allowing assessment of the effect of the rods' own thermal mass and surface area, independent of any phase change material. In Still-III, each of the ten rods was filled with 150 g of PCM, enabling the storage of latent heat as the PCM underwent melting during the day and solidification at night, thereby extending water production into the nighttime hours. In Still-IV, the ten rods were filled with NPCM at varying nanoparticle concentrations to evaluate the effect of nanoparticle loading on thermal performance: three rods contained NPCM with a 0.5% nanoparticle concentration, three rods

contained 0.75% concentration, two rods contained 1% concentration, and the remaining two rods contained 2% concentration (by weight in the PCM).

This graded distribution of concentrations allowed the influence of nanoparticle loading on heat storage and release behavior to be examined within a single still configuration. The complete schematic layout of the solar still, illustrating the basin geometry, glass cover orientation, and rod placement, is presented in Figure 1, while a photograph of the fabricated and instrumented experimental setup is shown in Figure 2, and the specifications are tabulated in Table 1.

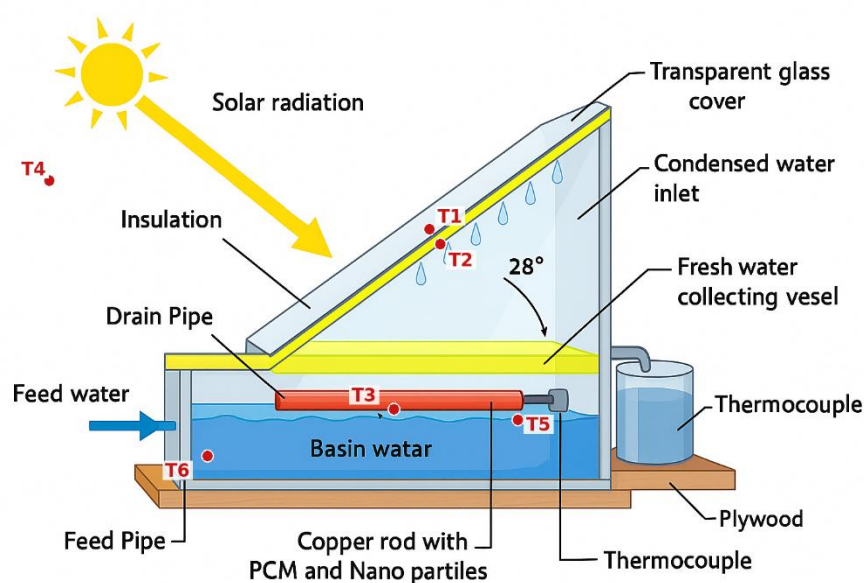


Figure 1. Schematic layout of experimental setup.

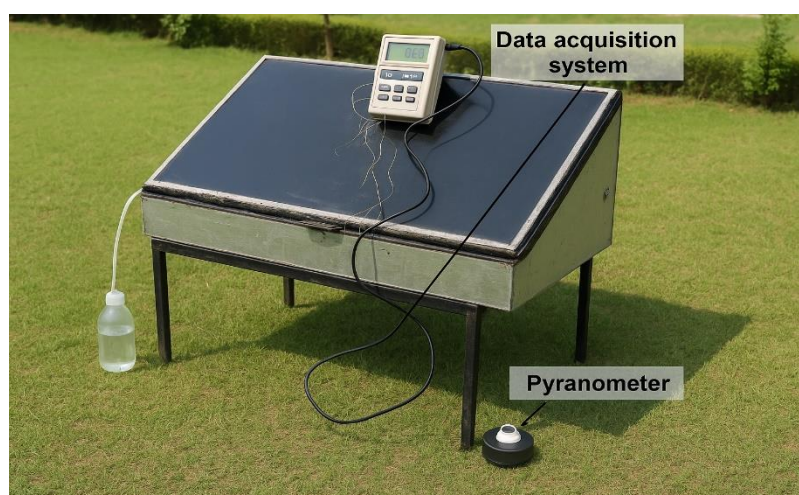


Figure 2. Actual view of experimental setup.

Table 1. Technical specifications of the experimental setup.

Component	Utilized materials	Dimensions/quantity
Frame	Wood	--
Basin	Galvanized iron	170 × 90 mm
Coating	Black paint	--
Insulation	Glasswool	5 mm each side
Glass cover	Transparent glass	8 mm thick
PCM	Parrafin wax	2 Kg
Nanoparticles	MXene	25 g
Storage Pipe	Copper	18 mm × 87 mm × 0.2 mm

3. Materials and preparation of NPCM

The latent heat storage medium utilized in this study was solid paraffin, possessing a melting temperature of 62 °C, procured from Aligarh, UP, India. MXene (Ti₃C₂) nanoparticles, with a total mass of 25 g, were obtained from SRL Pvt. Ltd., Mumbai, India. The selection of paraffin with a melting point of 62 °C was based on its thermo-physical compatibility with the anticipated operational temperature range of the solar still. This melting temperature facilitates efficient solid–liquid phase transition during daily thermal cycles, enabling effective latent heat absorption and release. Such behavior ensures enhanced thermal buffering capacity within the basin, thereby improving the stability of water temperature, accelerating evaporation rates, and ultimately augmenting the distillate yield. The key thermo-physical characteristics of the base PCM and the nanoparticle are summarized in Table 2. The thermal conductivity of the base PCM and the nano-enhanced PCM (NPCM) was experimentally measured using a transient measurement technique at representative operating temperatures. The results confirmed a measurable increase in thermal conductivity for the NPCM (0.297 W/m-K at 0.5 wt%, 0.316 W/m-K at 0.75 wt%, 0.335 W/m-K at 1 wt% and 0.387 W/m-K at 2wt%) compared to the pure PCM, which is consistent with the enhanced heat transfer behavior observed in the solar still experiments. These values are explicitly reported and discussed to establish a direct link between material properties and system-level performance.

Table 2. Thermophysical properties of the PCM and nanoparticles.

S.No.	Property	PCM (Parrafin)	Nanoparticles (MXene)
1	Appearance	whitish	Black
2	Thermal conductivity	0.207 W/m-K	75 W/m-K
3	Specific heat capacity	2.21 J/g-K (at 25 °C)	0.85 J/g-K (at 25 °C)
4	Density	0.88 g/cm ³	3.7 g/cm ³
5	Melting point	60–62 °C	--
6	Latent Heat	352 kJ/kg	--

Nano phase change material (NPCM) is a phase change material (PCM) enhanced with nanoparticles to improve its thermal conductivity and energy storage capacity. NPCMs are typically prepared using either the one-step or two-step method. In the one-step method, nanoparticles are dispersed during PCM synthesis, while in the two-step method, they are added afterward, enabling better nanoparticle distribution and superior thermal performance [29,30]. Solid paraffin wax (PW) was heated to a temperature slightly above its melting point to achieve complete liquefaction prior to nanoparticle incorporation. For each encapsulation tube, 142 mL of molten paraffin was utilized. MXene (Ti_3C_2) nanoparticles were dispersed into the liquid paraffin at weight concentrations of 0.5 wt%, 0.75 wt%, 1 wt%, and 2 wt%, respectively. Throughout the mixing process, the paraffin temperature was maintained above its melting point to ensure stable dispersion and prevent re-solidification. To enhance nanoparticle homogeneity and minimize agglomeration, the nano-PCM suspension was mechanically agitated using a magnetic stirrer operating at 350 rpm for 60 min. This procedure ensured uniform nanoparticle distribution and improved thermal conductivity of the resulting NPCM composite. The dispersion stability of nanoparticles within the PCM was assessed through a combination of controlled preparation procedures and post-processing observations. Mechanical stirring followed by ultrasonication was employed to promote uniform dispersion. Visual stability tests conducted over repeated heating–cooling cycles showed no noticeable sedimentation or phase separation during the experimental duration, suggesting acceptable short-term stability of the NPCM. Nevertheless, the possibility of gradual agglomeration under long-term cyclic operation cannot be ruled out and is acknowledged as a limitation.

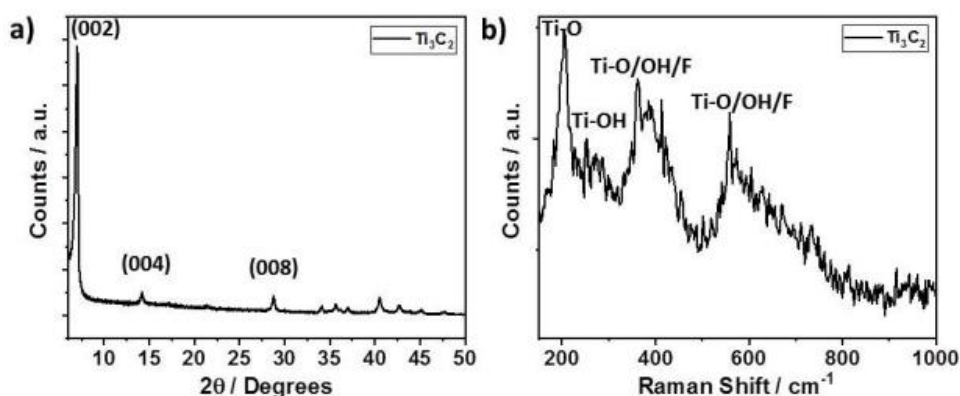


Figure 3. Structural characterization of the MXene (Ti_3C_2). a) XRD diffractogram b) Raman spectrum.

To confirm the successful synthesis and structure of MXene, X-ray diffraction (XRD) and Raman spectroscopy, were performed, and the results are presented in Figure 3. The XRD pattern exhibits a sharp diffraction peak at 7.1° (2θ) corresponding to the (002) plane (Figure 3a), indicating an interlayer spacing of approximately 14.5 Å. This enlarged spacing is characteristic of HCl–fluoride salt etched Ti_3C_2 MXene and agrees well with other reported results. The presence of additional (00l) reflections, such as (004) and (008), further confirms the layered structure and successful formation of Ti_3C_2 MXene. Raman spectroscopy (Figure 3b) provides additional structural verification, with the obtained spectra closely matching those reported in the literature. The peaks located at 207 cm^{-1} and 270 cm^{-1} correspond to E_g vibrational modes associated with Ti–O and Ti–OH surface groups, respectively.

Furthermore, broad peaks centered around 390 cm^{-1} and 580 cm^{-1} are attributed to vibrational modes related to Ti–O, Ti–OH, and Ti–F surface terminations, which are commonly observed in Ti_3C_2 MXene due to the chemical etching process. These results collectively confirm the successful synthesis of layered Ti_3C_2 MXene with typical surface functional groups.

In addition, basic material characterization evidence has been incorporated to support the NPCM formulation. Representative microstructural observations (e.g., SEM images) are provided to illustrate nanoparticle distribution within the PCM matrix (See Figure 4). The SEM image of the MXene-based PCM reveals characteristic wrinkling and stretching of the MXene sheets within the paraffin wax matrix. This morphology is indicative of the laminar, two-dimensional structure of MXene, which conforms closely to the surrounding paraffin and promotes strong interfacial contact between the filler and the PCM. Such a sheet-like configuration is expected to facilitate the formation of continuous thermal transport pathways within the composite, thereby contributing to the enhancement of the thermophysical properties of the PCM. Furthermore, repeated melting–solidification cycles were conducted to qualitatively assess thermal reliability, with no significant deviation in melting behavior observed over the tested cycles. While these characterization efforts are limited in scope, they provide initial validation of the material preparation and support the experimental findings.

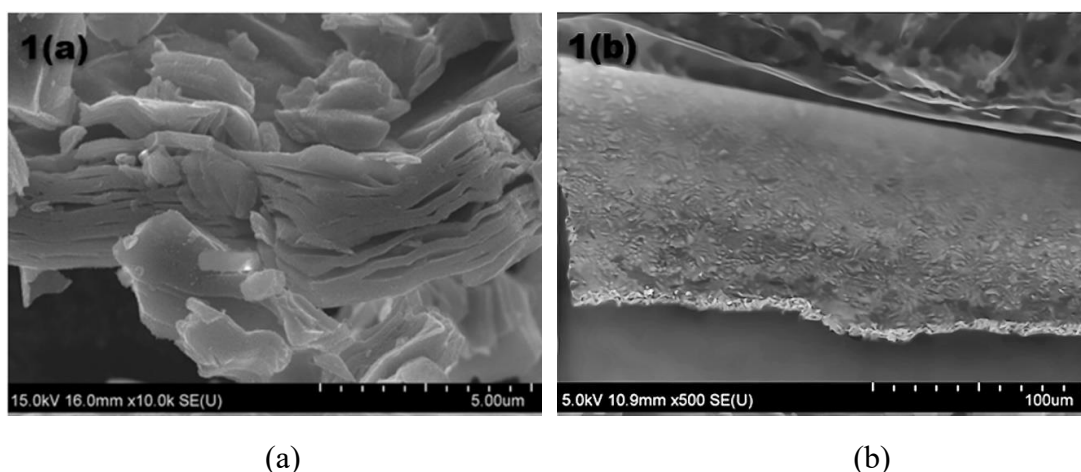


Figure 4. SEM micrographs of the (a) Pure Mxene and (b) Mxene/Paraffin wax-based nanocomposite.

Long-term stability of thermally enhanced composites is a prerequisite for their reliable using in the energy storage applications. The reliability of the composites can be determined by demonstrating that the thermal conductivities are stable. Table shows the thermal conductivity of the 2 wt.% Paraffin wax/ Ti_3C_2 composites after they have undergone 5, 10, 15, and 20 heating/cooling cycles. Table 3 shows that the maximum variation in thermal conductivity is less than 1% over the performed heating/cooling cycles. This shows that Paraffin wax/ Ti_3C_2 composites are highly stable and can be used in energy storage applications.

Table 3. Variation in Thermal conductivity with no. of cycles at 2wt% concentration.

Heating/Cooling cycles	0	5	10	15	20
Thermal conductivity (W/m-K)	0.385	0.384	0.382	0.384	0.383

The chemical structures of pure paraffin wax and PW/MXene nanocomposites were analyzed using FTIR spectroscopy, as shown in Figure 5. The inset of Figure 5 presents the FTIR spectrum of Paraffin Wax, showing characteristic peaks at $\sim 827\text{ cm}^{-1}$ corresponding to Ti–O vibrations and a prominent peak at $\sim 3328\text{ cm}^{-1}$ attributed to O–H stretching from intercalated water. In the PW/MXene nanocomposites, characteristic peaks associated with C–H, C–O, and C=C functional groups are observed. A peak at 2948 cm^{-1} occurs due to C–H symmetric bonding, while a peak at 1433 cm^{-1} occurs due to CH_2 bending, while the peak found at 1060 cm^{-1} is due to C–O stretch and O–H bend. The positions of the characteristic peaks remain nearly unchanged with increasing MXene loading, indicating that MXene addition does not significantly alter the chemical structure of Paraffin wax and that the interaction between MXene and paraffin wax is mainly physical.

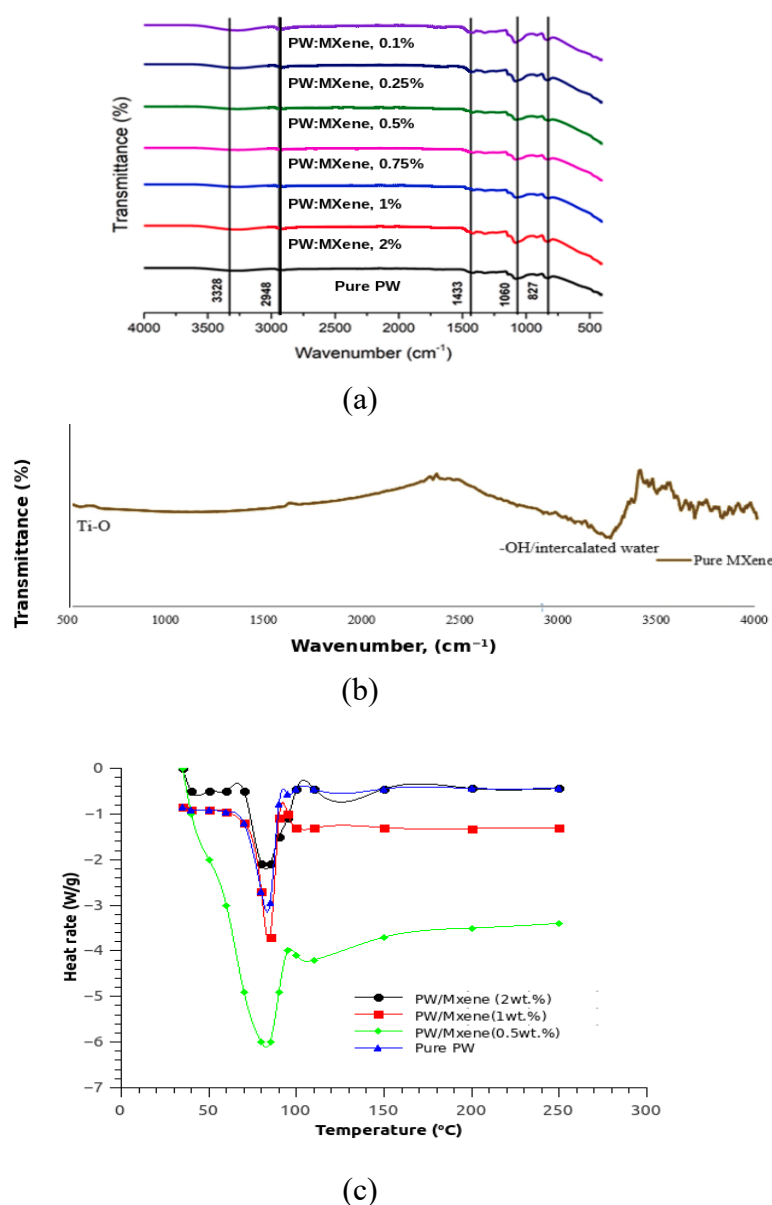


Figure 5. (a) FTIR spectra of Paraffin Wax(PW) and Mxene/Paraffin wax nanocomposites with varying MXene loading; (b) FTIR spectra of pure MXene; (c) DSC curves for PW/MXene nanocomposites and pure PCM.

Figure 5(b) presents the FTIR spectrum of pure MXene used in this work, showing the peaks for Ti-O at $\sim 530\text{ cm}^{-1}$ and prominent peak for O-H group at $\sim 3250\text{ cm}^{-1}$ from the intercalated water in the MXene.

Differential scanning calorimetry (DSC) was used to characterize the enthalpy and melting point of the synthesized paraffin wax (PW)/MXene nanocomposites and the pure PCM. Figure 5(c) presents the enthalpy results for pure paraffin wax and for nanocomposites containing different mass fractions of MXene flakes. The experimentally measured melting point of pure PW was $62.5\text{ }^{\circ}\text{C}$, which agrees well with the value reported by the PCM supplier. With the addition of MXene nanoparticles, the melting point increased slightly, reaching $67.7\text{ }^{\circ}\text{C}$ at the highest MXene concentration tested (2 wt.%). This modest increase can be attributed to interfacial interactions between the high-surface-energy paraffin wax molecules and the high-surface-area MXene nanoparticles. The rise in melting point further supports the proposed mechanism underlying the enhancement in specific heat capacity.

4. Observation and data collection

A LOGBOX-SD data logger was utilized to acquire and store solar irradiance and temperature data throughout the experiment. NTC thermistors rated for operation up to $150\text{ }^{\circ}\text{C}$ were employed as temperature sensors. Six thermocouples were installed at critical measurement points (see Figure1): the upper and lower surfaces of the glass cover (T1 and T2), the midpoint of the copper rod (T3), the ambient environment (T4), the evaporation interface (T5), and within the basin water (T6). Data were recorded at 30-minute intervals to ensure accurate thermal performance monitoring. Measurement of the distillate yield was done with a measuring cylinder. Technical specifications of the instruments used are provided in Table 4. Uncertainty analysis was conducted to evaluate the reliability of measured parameters such as solar radiation, temperature, water depth, and distillate output in the solar still experiment. Evaluating experimental uncertainty is essential for ensuring the reliability of solar desalination studies, as accurate measurements underpin system performance and efficiency analyses. In this work, the uncertainties of key instruments were assessed, with the solar radiation sensor (Pyranometer) exhibiting an uncertainty of $\pm 1\text{ W m}^{-2}$ and the temperature sensor showing a precision uncertainty of $\pm 0.01\text{ }^{\circ}\text{C}$. These low uncertainty levels confirm the reliability of the experimental data, indicating that the observed performance trends remain robust within the estimated uncertainty limits. The experimentally recorded productivity uncertainty and efficiency uncertainty were $\pm 1.42\text{ }^{\circ}\text{C}$ and $\pm 1.85\%$, respectively.

Table 4. Technical specifications of instruments used in experimental setup.

S.No.	Instrument used	Parameter	Accuracy	Range	Least count	Uncertainty
1	Pyranometer	Solar intensity	$\pm 1\text{ W/m}^2$	4000 W/m^2	1 W/m^2	$\pm 1\text{ W/m}^2$
2	Thermistor	Temperature	$\pm 0.1\text{ }^{\circ}\text{C}$	$150\text{ }^{\circ}\text{C}$	$0.1\text{ }^{\circ}\text{C}$	$\pm 0.1\text{ }^{\circ}\text{C}$
3	Measuring Beaker	Distillate output	$\pm 0.01\text{ L}$	1 L	0.01 L	$\pm 0.01\text{ L}$
4	Measuring tape	Length	$\pm 12\text{ cm}$	10 M	0.1 cm	$\pm 0.1\text{ cm}$

Experiments were conducted on clear sunny days between 09:00 and 17:00 h from March to May. Measurements were restricted to this period as solar radiation, the primary heat source, declines

significantly after 17:00 h. During daytime operation, the phase change material (PCM) absorbed excess heat and released it gradually during cooler nighttime hours, thereby extending the solar still's operation and improving thermal efficiency, especially under conditions of prolonged sunlight and low nocturnal temperatures. Consequently, data collection beyond 17:00 h was omitted as it does not contribute to understanding the solar-driven performance. Temperatures of the copper rod, basin water, glass cover, evaporative surface, and ambient air were recorded using NTC thermistors (range up to 150 °C). The distillate output was measured with a calibrated beaker, and solar irradiance was monitored using a pyranometer (make: Kipp & Zonen). The measurement uncertainties are summarized in Table 3.

The efficiency of the solar still was evaluated for all considered configurations. The daily energy efficiency of the system was determined using the following expression [31]:

$$\eta = \frac{m_d h_{fg}}{I_t A} \times 100 \quad (1)$$

where:

η —daily energy efficiency of the solar still (%);

m_d —mass of distillate water produced during the day (kg);

h_{fg} —latent heat of vaporization of water ($\text{kJ} \cdot \text{kg}^{-1}$);

I_t —total solar radiation incident on the still during the experimental period ($\text{kJ} \cdot \text{m}^{-2}$);

A —effective basin area of the solar still (m^2).

This relation represents the ratio of useful thermal energy utilized for water evaporation to the total solar energy incident on the basin surface, providing a quantitative measure of the system's thermal performance. The productivity of the solar still (P) is defined as the relative enhancement in the yield of the modified still compared to the conventional still, and is expressed as [32]:

$$P = \frac{M_m - M_c}{M_c} \quad (2)$$

where:

P —productivity improvement ratio;

M_m —daily distillate yield of the modified solar still (kg);

M_c —daily distillate yield of the conventional solar still (kg).

This parameter quantifies the percentage improvement in freshwater production achieved through system modifications relative to the baseline conventional configuration.

5. Results and discussion

The experimental results obtained from the conventional, PCM-integrated, and nano-PCM-integrated solar stills are presented and analyzed in this section. This multi-rod design was intended to control for day-to-day weather variability by testing all concentrations under the same ambient conditions, but we know that it does not eliminate position-related bias. The investigation focuses on the influence of solar irradiance, basin water temperature, and distillate yield on the overall performance of the systems. Figure 6 illustrates the hourly variation of solar irradiance recorded during the experimental day, showing a gradual increase from 09:00 h and reaching a peak value of approximately 1180 W/m^2 at 13:00 h, followed by a steady decline toward evening. This trend corresponds to typical clear-sky

solar radiation behavior, directly affecting the thermal response of the basin and subsequent evaporation–condensation processes. The comparative performance analysis demonstrates that the incorporation of PCM and nano-PCM enhances heat retention and maintains higher basin water temperatures during periods of declining solar intensity. These improvements result in prolonged evaporation rates and increased distillate productivity compared to the conventional still [33–35].

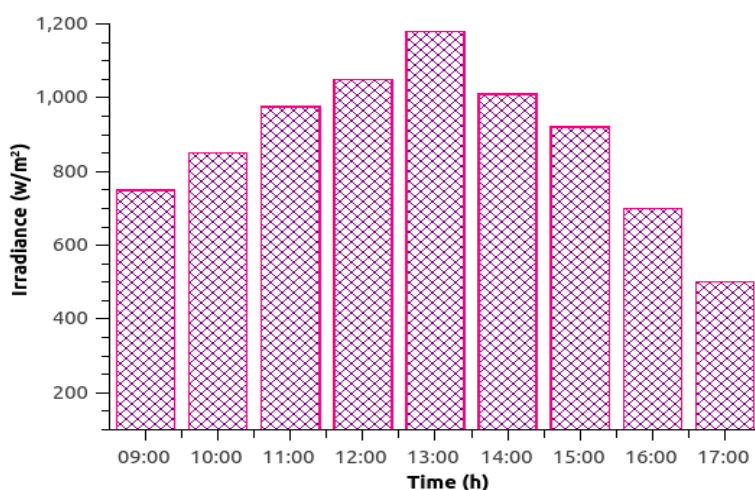


Figure 6. Solar irradiance trend over time for the conventional still configuration.

5.1. Temperature distribution for different types of solar stills

The comparative thermal performance analysis was conducted at a fixed water depth of 1 cm under identical environmental conditions for solar stills integrated with NPCM and PCM rods, as well as for stills equipped with clean rods and the conventional design. Figures 7–11 illustrate the temperature variations of water, basin, glass, and rods, along with ambient and evaporation temperatures and solar radiation for the four still configurations. Solar radiation increased steadily until noon, reaching its peak, and then gradually declined toward evening. For the conventional still (Figure 7), the maximum temperatures of the glass, evaporation, and basin were 61.2 °C, 67.1 °C, and 65.3 °C, respectively. In contrast, the still with clean rods (Figure 8) recorded higher peak temperatures, with water at 67.9 °C, glass at 63.9 °C, evaporation at 68.6 °C, and basin at 68.3 °C. In Figure 9, the still with PCM rods exhibited peak temperatures of 72.9 °C for water, 67.8 °C for glass, 74.2 °C for evaporation, and 72.8 °C for the basin. For the still with NPCM rods (Figure 10), the corresponding maximum temperatures were 77.8 °C, 81.2 °C, and 85.7 °C for the glass, evaporation, and basin, respectively. The highest rod temperatures for the empty, PCM, and NPCM cases were 72.6 °C, 73.5 °C, and 87.7 °C. The PCM used in all modified stills operated above its melting point, ensuring effective energy storage during the charging phase. Around noon, the PCM began melting, resulting in noticeable temperature differences between the basin water and glass surfaces.

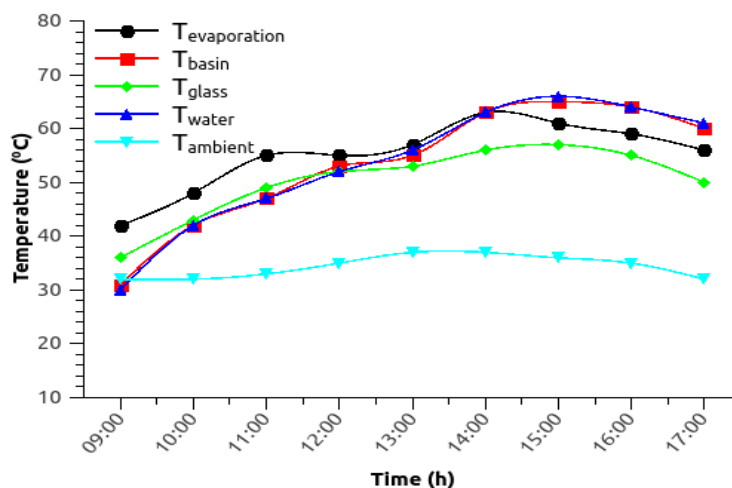


Figure 7. Temporal temperature distribution for a conventional solar still.

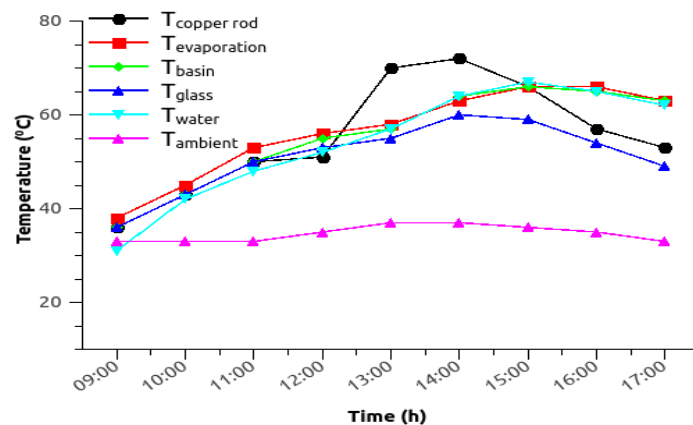


Figure 8. Temporal temperature distribution for the solar still with empty copper rods.

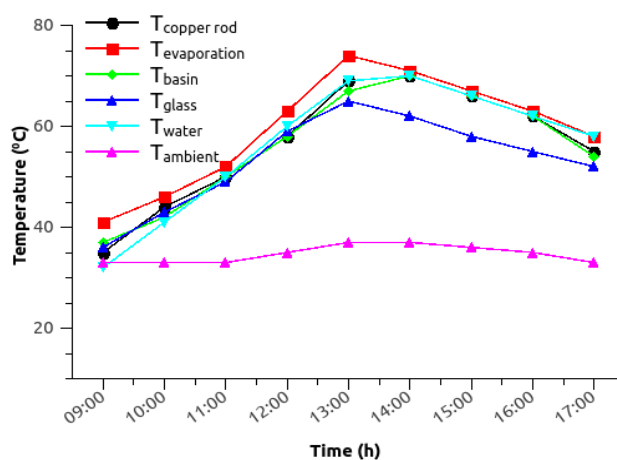


Figure 9. Temporal temperature distribution for the solar still integrated with PCM filled rods.

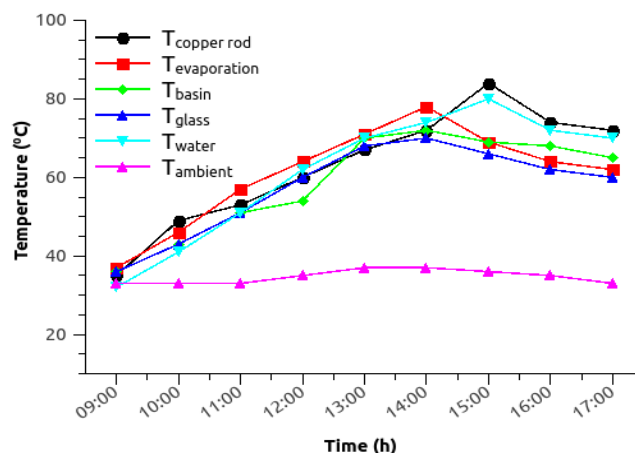


Figure 10. Temporal temperature distribution for the solar still integrated with nano-PCM filled rods.

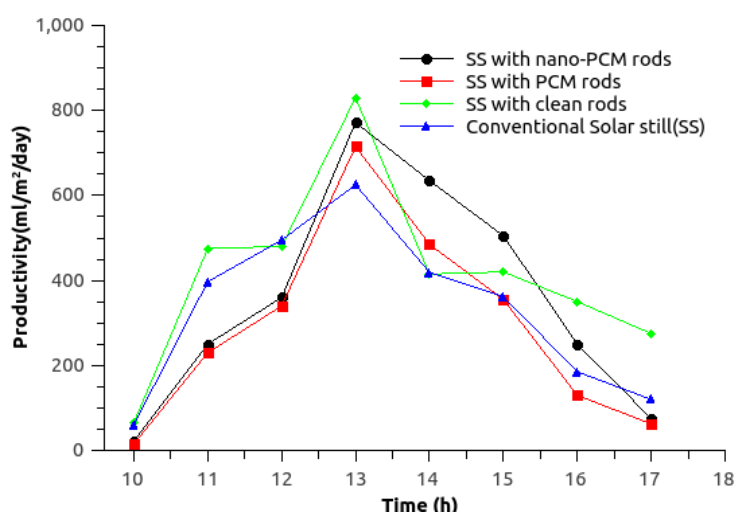


Figure 11. Hourly output of different type of solar still.

Physically, the higher temperatures observed in PCM- and NPCM-based stills were attributed to the enhanced heat storage and transfer capabilities of the encapsulated materials. During the charging period, the PCM absorbed excess thermal energy and released it gradually during the discharging phase, maintaining elevated temperatures for a longer duration. The inclusion of nanoparticles further improved the thermal conductivity of the PCM, facilitating faster heat diffusion throughout the storage medium. Consequently, the basin water in the NPCM still experienced more uniform and sustained heating, promoting greater evaporation rates and improved overall distillation performance compared with the conventional and empty-rod stills. The glass temperature may have exceeded the basin temperature during transient operating conditions due to direct solar absorption by the glass, latent heat release during vapor condensation, and the higher thermal inertia of the basin water. Reduced convective losses from the glass under low wind conditions could further amplify this effect. The

multi-concentration arrangement in Case 4 was adopted to screen a range of loadings within a single still under identical weather conditions, but since all rods shared the same basin water, the reported yield and temperature values reflect the aggregate response of the still rather than the isolated effect of any single concentration.

Figure 11, depicts the hourly productivity of the four still configurations from 9:00 am to 5:00 pm. The productivity of each still was primarily governed by the rate of heat absorption from solar radiation, which peaked around 13:00 pm and gradually decreased after 13:30 pm. As a result, the distillate yield increased steadily until approximately 13:00 pm, followed by a gradual decline toward evening. Table 5 shows the nighttime performance of the PCM- and NPCM-based stills. No significant yield was observed from the conventional and clean-rod stills after 5:00 pm, whereas the PCM and NPCM stills continued to produce distillate due to the latent heat released during the discharging phase.

Table 5. The productivity of different solar still configurations during diurnal and nocturnal operation.

Type of still	Day Time (Productivity kg/m ² .day)	Night Time (Productivity kg/m ² .day))	Total (Productivity kg/m ² .day))
Conventional Solar Still (SS)	2.66	----	2.66
SS with empty rods of copper	3.31	----	3.31
SS with PCM filled rods	2.33	1.29	3.62
SS with nano-PCM rods	2.86	1.52	4.38

The conventional still exhibited lower productivity than the still integrated with empty copper rods, as the presence of copper enhanced solar radiation absorption during daytime operation (09:00–17:00 h). The improved absorptivity of copper contributed to higher distilled water yield in the empty-rod configuration compared to the PCM- and NPCM-based systems. Nevertheless, the PCM- and NPCM-filled rods introduced latent heat storage functionality, supporting extended evaporation during off-sunshine hours. The NPCM still demonstrated superior productivity over the PCM configuration during day and night due to the enhanced thermal conductivity and phase transition behavior imparted by nanoparticles. Consequently, stored heat was effectively discharged between 17:00 and 09:00 h, enabling continued freshwater generation. In contrast, the conventional and empty-rod stills remained productive only under active solar radiation [36].

Latent heat storage in PCM promoted prolonged heat release after sunset by maintaining relatively elevated basin water temperatures. During the melting phase of NPCM, water temperature remained higher than in the PCM still, sustaining a larger water-to-glass temperature gradient during daytime, which diminished gradually during nighttime. This supported continued evaporation in the discharge period. The daytime productivity of the conventional and empty-rod stills was 2.66 and 3.31 kg/m²·day, respectively, exceeding that of the PCM (2.33 kg/m²·day) and NPCM (2.86 kg/m²·day) systems. However, the NPCM configuration achieved the highest overall daily productivity, attributed primarily to its significantly enhanced nighttime yield.

A conventional still integrated with empty copper rods, a PCM-enhanced still, and an NPCM-integrated still exhibited total daily freshwater productions of 3.31 kg/m², 3.62 kg/m², and 4.38 kg/m², respectively. The incorporation of nanoparticles in the PCM further improved thermal storage behavior, resulting in a 20.94% enhancement in nighttime productivity for the NPCM still

compared to the PCM still. The overall efficiency of a solar still was quantified as the ratio between the thermal energy necessary to generate a specified amount of distilled water and the total incident solar energy on the system. The corresponding values are presented in Table 6.

Table 6. Overall efficiencies of different stills.

Type of still	Overall efficiency (%)
Conventional Solar Still (SS)	47.20
SS with empty rods of copper	59.15
SS with PCM filled rods	62.85
SS with nano-PCM rods	70.15

According to Table 6, the daily energy efficiency of the conventional still, the still integrated with empty copper rods, the PCM still, and the NPCM still was 47.20%, 59.15%, 62.85%, and 70.15%, respectively. The incorporation of thermal energy storage materials and enhanced heat absorption significantly improved evaporation and distillate production. Consequently, the total productivity of the still with empty rods, PCM still, and NPCM still increased by 24.29%, 36.19%, and 65.00%, respectively, when compared with the conventional solar still.

Table 7. Summary of research comparisons.

S.No.	Configuration of still	Material	Improvement in Productivity (%)	Efficiency	References
1	Inclined single-surface solar still	Paraffin wax	28.14	72.63	Dhindsa et al. [37]
2	Inclined single-surface solar still	Paraffin wax with aluminium oxide nanoparticles	60.53	----	Chaichan et al. [35]
3	Tubular solar still	Paraffin wax with graphene nanoparticles	53.91	50.85	Kabeel et al. [14]
4	Inclined single-surface solar still	Paraffin wax with aluminium oxide nanoparticles	60.37	68.29	Murali et al. [38]
5	Inclined single-surface solar still	Paraffin wax with silica nanoparticles	51.22	----	Kumar et al. [21]
6	Inclined single-surface solar still	Paraffin wax with Mxene nanoparticles	65	70.15	Present work

A comparative assessment between the present investigation and reported works was carried out to validate the performance of the proposed elevated single-slope solar still, as summarized in Table 7. It gives the reader a general sense of how our results compare with reported NPCM solar still studies. The analysis revealed that the integration of paraffin wax with MXene nanoparticles in this study

achieved a remarkable 65% enhancement in productivity and an overall efficiency of 70.15%. The achieved improvement is comparable with stills having different baseline condition and geometrical configurations reported in earlier research [39]. For example, Dhindsa et al. [37] obtained a 28.14% improvement with paraffin wax alone, while Kumar et al. [21] and Kabeel et al. [14] reported respective productivity enhancements of 51.22% and 53.91% using silica and graphene nanoparticles. Furthermore, Chaichan et al. [35] and Murali et al. [38] achieved approximately 60% enhancement with Al_2O_3 -based PCM systems, corresponding to efficiencies of 68.29%. The superior thermal performance observed in this work can be attributed to the high thermal conductivity and large surface area of MXene nanoparticles, which promote faster heat transfer, more uniform temperature distribution, and greater latent heat storage within the PCM [40,41]. The interconnected MXene network, combined with reduced interfacial thermal resistance, facilitates efficient heat conduction from the absorbing surface to the evaporation interface while minimizing energy losses at the MXene–matrix boundaries. This mechanism explains the observed increase in effective thermal conductivity and the corresponding improvement in evaporation rate and freshwater yield [42–44]. Overall, the proposed design represents a clear advancement over previously reported systems, underscoring its potential for enhancing freshwater production and energy efficiency in solar desalination applications [42].

5.2. Costing methodology for different solar still

A cost analysis was carried out based on the presented method [45,46] for all the experimental setups considered in this paper. The prevailing approach in the literature computes an annualized cost of ownership and divides it by annual water yield to obtain a levelized Cost Per Liter (CPL). The steps are: Determine capital cost (CC): basin, glass cover, insulation, frame, PCM, nanoparticle additive, and any auxiliary components (reflector, external condenser, heating coil, etc.). Estimate salvage value (SV), typically 10–20% of capital cost at end of life. Apply the capital recovery factor (CRF) using an assumed interest rate (i) and system life (n , years) to annualize capital cost: $\text{CRF} = i(1 + i)^n / [(1 + i)^n - 1]$. Add annual maintenance cost (AMC), often taken as a fixed percentage (e.g., 15%) of annualized capital cost. Compute total annual cost: $\text{AC} = \text{CC} \times \text{CRF} - \text{SV} \times \text{sinking-fund factor (SFF)} + \text{AMC}$.

Divide by annual freshwater yield (liters/year) to obtain Cost Per Liter (CPL) = $\text{AC} \div \text{Annual Yield}$.

The following representative assumptions were used for calculations, Interest rate (i) is taken as 10%, Desalination system life (n) is taken as 10 years, and salvage value is taken as 10% of the capital cost. Operating days per year for solar still is considered as 300 days (accounts for cloudy/rainy days).

Nano-PCM integration is consistently shown, across a wide range of still geometries and climates, to lower the levelized cost of freshwater production relative to conventional and plain-PCM solar stills. To illustrate the methodology, consider a small single-slope basin still (1 m² absorber area) built in four versions: a conventional still, a still with empty copper rods, still with 2 kg of paraffin wax filled rods, and PCM enhanced with 2 wt% MXene nanoparticles (see Table 8). Even though the nano-PCM still costs about 29.6% more to build, its ~64.6% higher daily yield brings its cost per liter down to roughly \$0.0239/L versus about \$0.0304/L for the conventional still, an improvement of around 21.4%. The economic benefit stems primarily from higher round-the-clock yield rather than from lower capital cost, nano-PCM stills cost more to build but pay that difference back quickly, typically within a few months to about a year, through increased distillate output.

Table 8. A summary of cost analysis on considered setups.

Items	Conventional Still	Still with empty copper rods	Still with PCM filled copper rods	Still with NPCM filled copper rods
Basin, glass, frame, insulation	\$120	\$120	\$120	\$120
PCM (paraffin wax, ~2 kg)	\$0	\$0	\$10	\$10
Nanoparticle additive (Mxene 2 wt%) (40 g)	\$0	\$0	\$0	\$20
Miscellaneous/fitings	\$15	\$25	\$25	\$25
Total capital cost (CC)	\$135	\$145	\$155	\$175
Daily yield (L/m ² /day)	2.66	3.31	3.62	4.38
Annual yield (300 days)	798	993	1086	1314
Annualized cost ($0.180 \times CC$)	\$24.3	\$26.1	\$27.9	\$31.5
Approx. Cost per Liter	\$0.0304	\$0.0262	\$0.0256	\$0.02

6. Conclusions

In this study, we experimentally evaluated the performance of a solar still integrated with nano-phase change material (NPCM)–filled copper rods, benchmarking it against conventional, empty-rod, and PCM-based configurations. Our results confirm that dispersing nanoparticles within the PCM meaningfully improves the storage medium’s thermo-physical behavior, enhancing heat retention and translating into a measurable gain in distillate yield. During daytime operation (9:00 am–5:00 pm), the conventional still produced an average yield of 2.66 kg/m²·day, compared to 3.31, 3.62, and 4.38 kg/m²·day for the empty-rod, PCM, and NPCM configurations, respectively. The advantage of latent heat storage became particularly evident after sunset: the PCM-based still continued producing 1.29 kg/m² of distillate at night, while the NPCM-based still yielded 1.52 kg/m², reflecting the improved heat retention and release characteristics imparted by the nanoparticles. This was further supported by thermal measurements, which recorded consistently higher rod temperatures in the NPCM configuration than in the PCM and empty-rod systems, indicating more effective heat absorption and storage. Correspondingly, overall energy efficiency rose from 47.20% for the conventional still to 70.15% for the NPCM-based still, underscoring the combined benefit of enhanced thermal conductivity and extended heat release on total system performance. The cost of fresh-water production from the solar still setup conventional, with empty rods, with PCM filled rods and nano-PCM filled rods were obtained as 0.0304, 0.0262, 0.0256 and 0.0239 \$/liter, respectively. In summary, the findings demonstrate that NPCM integration offers potential to enhance solar still productivity and efficiency cost effectively under the tested conditions.

7. Limitation and future scope

Despite these promising results, the study has several limitations that warrant acknowledgment. The experiments were conducted over a limited duration and under a specific set of climatic conditions, and did not capture full sunrise-to-sunset behavior, which may constrain the generalizability of the

findings to other locations, seasons, or diurnal cycles. Long-term aspects such as the thermal stability of the nano-enhanced PCM, nanoparticle agglomeration under repeated thermal cycling, and potential material degradation over extended use fall beyond the scope of this work, as does post-operation characterization of the NPCM to assess its condition after extended exposure. In future work, researchers should focus on optimizing nanoparticle concentration and improving dispersion stability to enhance the thermal performance of NPCM-based solar stills, using separate, uniformly-loaded stills to properly isolate concentration effects. Extended trials that capture full sunrise-to-sunset behavior, along with long-term studies on thermal reliability and cyclic stability, are needed to establish durability under real operational conditions. Integrating NPCM systems with hybrid configurations, such as photovoltaic-thermal or waste-heat-recovery units, could further improve overall efficiency. Design optimization of basin geometry and cover angle may enhance heat transfer and condensation performance. Finally, economic evaluation, life-cycle assessment, and large-scale field testing will be essential for translating this technology toward practical implementation.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

The authors declare no conflicts of interest.

Author contributions

Conceptualization: Mohammad Salim; Methodology: Syed Mohd Yahya, Mohammad Salim, Mohd Seraj; Software: Azhar Jamil; Validation: Syed Mohd Yahya, Mohammad Salim; Formal analysis: Syed Mohd Yahya, Arshad Hussain Khan; Investigation: All authors; Data curation: Mohammad Salim; Writing—original draft preparation: Mohammad Salim; Writing—review and editing: All authors; Visualization: All authors. All authors have read and agreed to the published version of the manuscript.

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