Applied Engineering Letters Vol.10, No.3, 146-159 (2025) e-ISSN: 2466-4847

ENHANCED THERMAL PERFORMANCE ANALYSIS OF SINGLE AND DOUBLE SLOPE SOLAR STILLS COATED WITH TiO_2 NANOPARTICLE-INFUSED NANOPAINT

UDC:621.311.243:628.165
Original scientific paper https://doi.org/10.46793/aeletters.2025.10.3.3

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

[1]Research Scholar, Department of Mechanical Engineering, Poornima University, Jaipur, Rajasthan, India
[2]Department of Mechanical Engineering, Poornima University, Jaipur, Rajasthan, India
[3]Department of Mechanical Engineering, Prestige Institute of Management and Research, Bhopal, India

Abstract:
With increasing freshwater scarcity worldwide, due to rapid population growth, it is difficult to maintain freshwater supplies; in places like Rajasthan and Gujarat in India, the desalination and purification techniques are proving to be the primary means of meeting the increasing demand for freshwater. However, the growing cost of fossil fuels is making typical distilling practices less competitive compared to other types. Therefore, this study shows that solar stills with TiO_2 nanocoating are a cost-effective and sustainable technique for the production of freshwater for regions with water scarcity due to their improved efficiency without the use of conventional energy sources. The experiments were conducted in May and March and included two types of solar stills with a 1 m² area and water depths of 10 mm, 20 mm, and 30 mm. Each configuration was subjected to three surface coatings of black paint, 2%, and 4% TiO_2 nanopaint coatings. The results showed that nanocoating increased thermal efficiency and water yield in single and double-slope solar stills. During March, the single-slope solar still with 4% TiO_2 nanocoating attained the maximum yield of 1811 ml/m² at a water depth of 10 mm, an improvement compared to 1377 ml/m² with simple paint. The yield for 20 mm and 30 mm water depths also increased significantly with the use of nanocoating. In March, the 4% nanocoated double slope still reached 2488 ml/m² at 10 mm of depth, greatly surpassing the 1970 ml/m² of the simple painted version. Due to elevated ambient temperatures and solar radiation, all stills performed better in comparison to March in the month of May. Double-slope solar stills proved to be more efficient than single-slope stills due to greater condensation surface area and better heat retention. Lower water depths led to higher output, as heating the water required significantly less thermal energy.

ARTICLE HISTORY
Received: 8 July 2025
Revised: 1 September 2025
Accepted: 15 September 2025
Published: 30 September 2025

KEYWORDS
Solar still, TiO_2 Nanoparticles, Nanocoating, Thermal Performance, Water Desalination, Single and Double Slope Configuration

1. INTRODUCTION

The accessibility of freshwater is a pressing global challenge, particularly in arid or semi-arid regions, because traditional sources are often limited, polluted, or difficult to obtain. As the global population continues to rise, securing access to safe drinking water has emerged as a major challenge, driving international organizations to initiate various remedial measures. Another major source of environmental pollution to the water is the widespread use of chemical fertilizers and pesticides in agriculture [1]. Water desalination and purification technologies can reduce the problem, but many of these, like reverse osmosis or multi-stage flash distillation, process it in a way that uses

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

too much energy and is prohibitively expensive, making them completely impractical in remote or developing areas. In this situation, solar distillation is a cheap and environmentally friendly method [2]. The major drawback, however, is that solar stills are extremely inefficient heaters and only produce a very small amount of water per day. This makes the approach unattractive from household, let alone large-scale, perspectives without significant enhancements. There exist several techniques aimed at increasing the efficiency of solar stills, such as incorporating phase change materials (PCM), external reflectors, or heat exchangers [3-5]. While effective, in some cases, these tried-and-tested techniques add complexity and require more maintenance, driving up the overall cost. Utilizing high absorptivity paints as surface coatings is a simpler approach that has been left largely unexplored [6]. Advanced materials such as nanofluids and nanocomposites have been shown to greatly enhance solar absorption and water productivity, yet very limited studies [7-10] have focused on applying nanoparticle-enhanced paint coatings to still's inner surface.

However, rising costs of fossil fuels are making traditional distillation practices less viable compared to other options. With this in mind, this study shows how solar stills with TiO_2 nanocoating can serve as a cost-effective and sustainable method for producing freshwater in areas where water is scarce, as they have better efficiency and do not require traditional energy sources. The experiments were conducted in May and March and included two types of solar stills with a 1 m^2 area and water depth of 10 mm, 20 mm, and 30 mm. Each configuration was subjected to three surface coatings of black paint, 2%, and 4% TiO_2 nanopaint coatings. The results showed that nanocoating increased thermal efficiency and water yield in single and double-slope solar stills.

Application of nanomaterials with stronger optical and thermal properties is one of the best ways to increase solar still efficiency [11]. The nanoparticles of aluminun oxide (Al_2O_3), copper oxide (CuO), titanium dioxide (TiO_2), and graphene oxide are recently popular due to their thermal conducting abilities and thus increasing the rate of heating and cooling in a solar still system [12-14]. The use of Al_2O_3 nanoparticles is advantageous due to their low cost, the improvement in thermal efficiency of the base fluids, micro-absorbers or basin coated materials, and their chemical stability [15,16]. These nanoparticles are effective in suspensions in PCMs or in coatings and paints as they increase the thermal storage, heat distribution, and efficiency during operation. More efficient energy storage and conversion have been developed with NEPCM or nano-infused phase change materials, which are created by infusing nanoparticles into traditional PCMs such as wax [17]. Agrawal et al. [18] performed an experimental investigation by incorporating nano-enhanced eutectic PCM on a double slope solar still and found an enhancement of 41% in average energy efficiency. These materials are proven to improve melting and solidification cycles as well as the storage capacity of heat. For example, CuO nanoparticles have been added to paraffin-based PCMs, resulting in an increase of up to 35% in freshwater production. In the same manner, the inclusion of aluminum nitride (AlN) and graphene oxide increases the system's ability to thermally respond and, therefore, significantly increases water yield. In experiments with AlN-water nanofluids and AlN-black coated surfaces, water yield was over 24%, demonstrating the great potential nanoparticles hold for enhancing solar desalination [19]. Kabeel et al. [20] investigated a pyramid-basin type solar still coated with TiO_2 nanoparticles dispersed in black paint and reported a 6.1% increase in yield compared to the conventional design. Alongside the progression of NEPCMs, other researchers have modified the advanced absorbing materials and coatings to enhance the absorption efficacy of basin liners in solar stills. The traditional option for basin coating is black paint, as it possesses high absorptivity. However, painting black surfaces with Al_2O_3 nanoparticles (known as nanocoating or nanopaint) results in hybrid surfaces with elevated thermal and optical properties [21]. The paints also increase solar absorption and surface temperatures, which quickens water evaporation and creates an effective thermal gradient between the water surface and the condensation cover, which is important for increasing distillation rates [22,23].

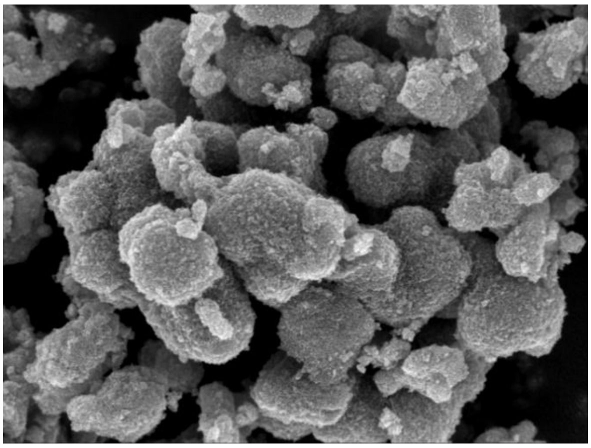
Moreover, double-slope solar stills, which are an improvement over single-slope designs, are evaluated for their ability to maintain full solar radiation reception throughout the day [24]. Both slopes are designed to face the sun from sunrise to sunset to maximize the operational hours and improve the collection of water. With the use of nanocoated basins or NEPCMs, double-slope solar stills are more thermally efficient and yield more water than single-slope stills [25]. Alongside innovations in materials and structures, researchers look into Auxiliary methods such as external reflectors, solar concentrators, photovoltaic-thermal (PV/T) modules, and thermoelectric generators (TEGs), which aim to increase energy input and improve thermal conditions in solar stills [26]. Although these systems are more effective, the additional components or energy sources required increase costs and complicate the systems. Therefore, the enhancement of passive solar stills through innovative material use seems to be, if not the most, one of the easiest and most scalable approaches, particularly in constrained-resource settings.

This research works towards a novel method for enhancing solar still performance by adding TiO_2 nanoparticles to black paint, which will be used to coat the basins of both single and double-slope solar stills. TiO_2 was selected for this study because of its abundant availability, chemical stability, and high thermal conductivity. Its superior optical and thermal properties increase absorption of solar energy and increase evaporation rates. In addition, TiO_2 can enhance the thermal conductivity and the integrity of the basin, resulting in higher freshwater productivity and greater stability of the operation over a long service life. Among other nanoparticles, TiO2 is a low-cost, non-toxic, and UV-resistant material that is very promising for sustainable and scalable solar desalination applications. Single and double-slope configurations with the same environmental conditions are tested to determine the best configuration for easy-to-use, practical installation. The objective of the current study is to address the combined impact of slope configuration along with nanoparticle-enhanced materials on the knowledge gap of passive solar desalination. While several studies have separately assessed NEPCMs and nanofluids or tested nanoparticle coatings independently of other variables, few have systematically compared both single- and double-slope designs employing nanocoated basin surfaces. The aim of the present study was to analyze the impacts of different types of coatings (simple black paint, 2% TiO_2 nanopaint and 4% TiO_2 nanopaint) and water depths (10 mm, 20 mm, and 30 mm) on the productivity and efficiency of the solar stills. The experimental procedure consists of TiO_2 nanopaint-coated and uncoated solar stills to measure water yield, along with thermal efficiency and temperature of the surfaces on solar stills over a set duration, while maintaining the climatic parameters to a controlled set.

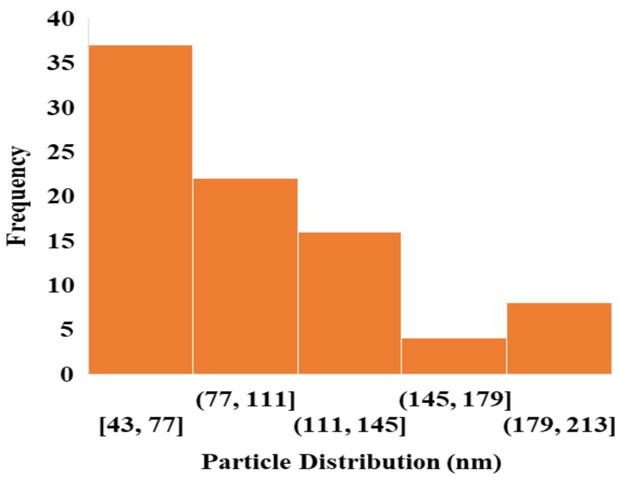
2. MATERIALS AND METHODS

2.1 Nanoparticle TiO_2

The synthesis and characterization of titanium dioxide (TiO_2) nanoparticles were done to analyze their morphology and particle size distribution with respect to their possible application in thermal energy storage and the enhancement of solar stills. The morphology of the synthesized TiO_2 nanoparticles was analyzed using a Scanning Electron Microscope (SEM) at a magnification of 30,000x and at an accelerating voltage of 5.0 kV. Fig. 1 demonstrates the SEM image captured, showing that the TiO_2 nanoparticles have an approximately spherical shape, which is prone to undergo agglomeration. These agglomerates point towards either strong van der Waals forces or surface interactions between the particles, which is rather typical in metal oxide nanoparticles. It appears that the surface of each particle is relatively rough, which may improve the surface area of PCM and thermal conductivity when the particles are added as fillers. This distinct granular morphology also provides additional evidence for the successful synthesis of nanoscale TiO_2. No visible cracks or fractures were observed, indicating some mechanical stability at a microscale.



a)



b)

Fig. 1b. a) SEM image of TiO_2 nanoparticles, b) Particle size distribution histogram of TiO_2 nanoparticles

Along with the morphological analysis, particle size distribution was evaluated quantitatively using the SEM data, and the corresponding results are displayed together with the SEM micrograph. The histogram illustrates that the smallest particles are around 43 nm, while the largest exceed 213 nm, showing a wide range. The data is divided into five groups of sizes (43, 77], (77, 111], (111, 145], (145, 179], and (179, 213] nm. Most of the nanoparticles cluster around the size 43-77 nm range with nearly 38 particles observed, suggesting the synthesis process was aimed at producing finer particles, which are advantageous in nanotechnology due to their high surface-to-volume ratio and reactivity. Furthermore, as the size of the particles increases, the number of particles sharply drops, having nominal counts in the 145–179 nm and 179–213 nm ranges. This data also illustrates that the sample does indeed consist chiefly of nanoparticles under 100 nm in diameter, confirming their identification as nanoscale TiO_2. The fact that the distribution is more or less uniform, but with a tail towards the larger particle sizes, is most likely the result of nucleation and growth kinetics that occurred during synthesis. A narrow distribution is quite important for thermal energy storage applications because the uniformity of thermal behavior is retained when integrating TiO_2 nanoparticles with PCMs. Not only the size of the particle but also the particle dispersion and stability within the base PCM matrix influence the thermal conductivity.

In summary, the analyses of SEM and particle size distribution substantiate the successful synthesis of TiO_2 nanoparticles with the specific characteristics to be used for advanced energy applications. Their nanoscale size and advantageous morphological characteristics render them ideal for significantly enhancing the thermal performance of solar stills by increasing energy absorption, retention, and conductivity. The morphological features and uniformity within composite materials pose high potential for effective dispersion without considerable agglomeration if appropriate surfactants or stabilization methods are incorporated during integration.

2.2 Normal and Nanopaint Microstructural Study

The long-term behavior of ordinary paint and TiO_2 nanoparticle paint, or “nanopaint,” was observed under the operating conditions of a solar still using SEM to analyze the surface morphology and degradation features for both types of paint. In Fig. 2, you can see how the solar still basin’s surface paint suffers dynamic degradation with time. After 5 days, 10 days, and 20 days of continuous solar radiation, water evaporation cycles, and submersion in saline water, the paint is observed to be actively peeling away. On the contrary, the SEM images in Fig. 3 illustrate the differences in surfaces coated with 2% and 4% TiO_2 nanopaint after 20 days of operation in terms of surface finish, topographical detailing, and microstructural robustness.

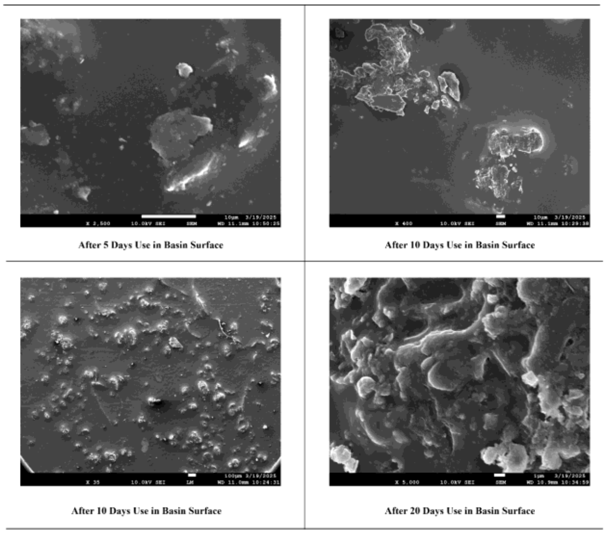


Fig. 2. Normal paint SEM analysis of basin surface

The SEM image of the conventionally painted basin surface after five days shows smooth regions with microcracks and irregularities, indicating moderate surface fatigue from thermal cycling and moisture nadir exposure. When the usage period increases to 10 days, the degradation appears to be more severe. This SEM stage captures dramatic flaking and paint detachment along with numerous voids and cracks. These features suggest the bond between the paint and the metallic basin substrate is weakening due to the cyclic expansion and contraction of the paint layer, along with the salt and water erosion, and environmental erosion.

After operating for 20 days, the normal paint has suffered a lot of damage. The surface has crystallized and blister-like structures as well as large-scale peeling is common. The coating appears brittle and porous, which are indicators of moisture ingress. Moisture ingress would accelerate the corrosive deterioration while compromising the thermal insulation of the basin. Defects of Texture (DOTs) microstructural failure denotes a greater amount of thermal and chemical stress over time, which means it would not work for applications such as solar stills, which require a lasting surface material and reflectors for the system to work efficiently.

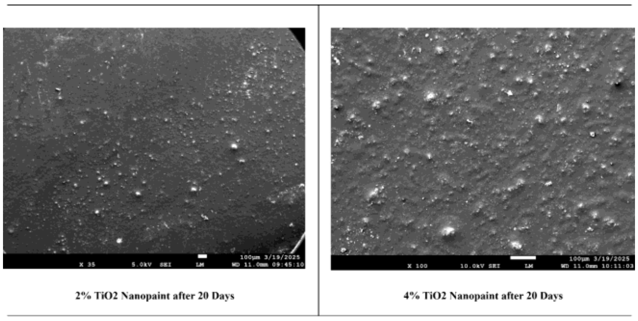


Fig. 3. TiO_2 mixed nanopaint (2% and 4% concentration) SEM images after 20 days of operation of the solar still

The nanopaint-coated surfaces (Fig. 4) SEM analysis shows completely different results. After 20 days of 2% and 4% TiO_2 nanopaint coatings under the same operational conditions, they have reached a similarly well-ordered and dense microstructure. The surface of the 2% TiO_2 nanopaint shows only slight exfoliation, which is quite remarkable. Sample surfaces seem to have a denser and more coherent upper layer as well as a crack-resistant layer, which improves the structural stability while diminishing the lack of environmental durability. These states are better due to the thermal stability and photocatalytic properties of the structurally stronger TiO_2, which does not break down under fierce solar radiation.

Fig. 4. Single and double slope solar still experiment setup (Location Bhopal)

In the SEM image, the 4% TiO_2 nanopaint displays an even better developed surface than the 2% variant, showcasing unparalleled surface smoothness and strength. The second 4% sample shows improved homogeneity where the nanoparticles are distributed more evenly, and the coarse texturing is no longer evident. It can be assumed that at this loading level, the degree of crosslinking in the paint matrix was increased, thus improving its adhesion, mechanical and thermal protection capabilities. In addition, the nanosized filler particles significantly decrease the void volume ratio, masking the weak interface in the paint film, which improves adhesion, packing density, and overall anchoring to the paint film.

Self-cleaning antifouling properties can be attributed to the TiO_2 nanoparticles, allowing less maintenance work to be done and increasing the lifespan of the solar still basin. The surface porosity, when comparing the two nanopaint samples to the normal paint, shows a significant decrease. Optically and thermally, the materials a lot slower to deteriorate. Porosity even further lowered thermal level losses, salt and water corrosion added protection and better resistance of the material's optical and thermal properties. The endurance of the solar basin is greatly enhanced by lowering the operational maintenance work required. Significant improvements in mechanical strength, thermal protection, and UV resistance are anticipated from the formulation of composite nanoclay paints, provided their performance proves to be satisfactory. Sun exposure usually leads to paint deterioration such as fading, chalking, and brittleness. The addition of a UV blocking agent such as TiO_2 will greatly improve the durability by protecting the material from harmful radiation. Overall, the SEM micrographs clearly demonstrate how the TiO_2-based nanopaint outperformed the conventional paint in terms of preserving surface integrity and resisting degradation under highly detrimental operating environments. The normal paint shows catastrophic microstructural failure in a mere 20 days, while the 4% TiO_2 nanopaint exhibits remarkable structural integrity. These results strongly imply that the application of nanotechnology to paints greatly improves the operational and service life efficiency of solar thermal systems. Thus, the expanding use of TiO_2 nanopaint in solar stills and other solar applications transforms it into a substitute for conventional coatings, which face severe material stability challenges under high temperature, moisture, and sunlight exposure.

2.3 Experiment Methods

The current study focuses on the fabrication and testing of two types of solar stills, single slope and double slope, to assess their thermal performance and productivity. The design of both solar stills incorporated an identical basin area measuring 0.6 m by 0.8 m, allowing for a consistent volume and surface area, which could be used for comparative evaluation. This experiment was performed on the terrace of Sagar Institute of Science Technology and Research in Bhopal, India, selected for its solar accessibility and monitoring convenience. The glass covers' slope angle is set to the latitude and longitude of Bhopal (23.25° N, 77.41° E) to achieve the optimal solar radiation for both types of still. With this glass slope alignment, the capture of solar energy and radiation was enhanced while achieving the former high evaporation rates. The single slope was still optimized for the Northern Hemisphere by southward tilting the glass cover, while the double slope still utilized symmetric glass covers inclined in opposite directions to effectively harness both morning and afternoon solar radiation.

One key aspect of the modern configuration of the experiment, Thermocol sheets, and aluminum foil served as a two-sided Thermal Insulation. This served to minimize the sides and bottom thermal losses while providing the sought-after temperature differences across the basin. This assists in retaining solar heat in the water body for as long as possible, which is critical in the improvement of the evaporation and condensation processes. A nano-enhanced coating (nanopaint) was also added to the basin. These paints were loaded with TiO_2 nanoparticles. This is due to the high thermal conductivity, UV resistance, and high superfialadsorbent of these nanoparticles. Some concentrations of these nanoparticles were tested, which were 2% and 4% to test the thermal storage rate and the evaporation rate of water. The purpose of the basin was to make the water evaporate, and to achieve this, the basin needed to be more absorptive to incident solar radiation. Therefore, the aim was to increase the heat energy to raise the water temperature.

The same volumes of saline solution were placed in both stills and maintained in identical external conditions for a specific period of time. The temperature of the air and water, the state of the basin's surface, and the amount of distillate produced each day were all meticulously measured with thermocouples, measuring cylinders, and data loggers. Each still's performance was assessed and compared, demonstrating the impact of slope design and nanopaint utilization on solar stills' productivity in central India's climate. The experimental measurements were conducted daily from 09:00 to 18:00 hours to capture the full variation in solar intensity. The distillate yield was additionally monitored during nighttime to evaluate the contribution of nanoparticles to extended operation. Solar radiation was measured using a TES-1333 solar power meter, while water, basin, glass, and ambient temperatures were recorded using K-type thermocouples connected to a multi-channel digital temperature indicator. The distilled water output was collected and measured at regular intervals using a graduated measuring cylinder.

2.4 Uncertainty Analysis

Analyzing uncertainty is essential for validating experimental results, as it involves checking the precision and accuracy of the results. It identifies potential sources of errors from measurement devices and methodologies used in the procedure.

In this research, focus was placed on uncertainty estimation for all key parameters to enhance the trustworthiness of the results achieved from the solar stills. The uncertainty is caused by imprecision concerning measurement tools, changes in the surrounding atmosphere, observational errors, and tolerable variations in the measuring devices. Values of uncertainty were determined by the methods provided, with the bounds of accuracy specified by the manufacturer, along with values of calibration, separately contemplating the accuracy limits and calibration data. Some values were picked from the device specification sheets, while some were derived from experiments. For the measurements which were done by thermocouples, graduated cylinders, and solarimeters, the absolute uncertainty for those measures was calculated by the following Eq.1:

$$u = \frac{a}{\sqrt{3}} \tag{1}$$

where are: *u* - represents the uncertainty value of each measuring instrument, and *a* - indicates individual values.

This method cites a possibility of instrument error occurring in one direction only, which is uniformly apportioned throughout the period of resolution for detection by the measuring device. Calibration of all measuring devices was conducted before the commencement of any experimental work. Temperature measurements with thermocouples (Type-K) were done with an accuracy of ±0.5°C. Water distillate collection and measurement were done with a graduated cylinder, which has a minimum measurable value of 1 ml. Solar radiation was measured with a pyranometer at an uncertainty of ±10 W/m². Table 1 shows the summary of calculated uncertainties for different parameters. Further evaluation of the system's cumulative uncertainty was performed with the use of propagation techniques to determine the overall confidence in the performance analysis of the solar stills. The values obtained suggest that the uncertainty ranges associated with each measured variable are within reasonable bounds, thereby confirming the completeness and dependability of the experimental configuration and its results. The holistic evaluation of system performance reaffirms the claim of the enhanced solar still performance with the application of nanopaint.

Table 1. Estimated Uncertainty in Experimental Measurements

Measured Parameter	Instrument Used	Least Count / Accuracy	Estimated Uncertainty
Water Temperature	Type-K Thermocouple	±0.5 °C	±0.29 °C
Glass Cover Temperature	Type-K Thermocouple	±0.5 °C	±0.29 °C
Ambient Temperature	Digital Thermometer	±0.5 °C	±0.29 °C
Solar Radiation	Pyranometer	±10 W/m²	±5.77 W/m²
Distillate Output	Graduated Cylinder	1 ml	±0.50 ml
Time	Digital Stopwatch	1 s	±0.50 s

3. RESULTS AND DISCUSSION

The results obtained for the productivity of the single and double-slope solar stills analyzed in Tables 2 to 5 have been assessed for the different operational conditions for the months of March and May. For three different water depths: 10 mm, 20 mm and 30 mm, the yield performance was noted alongside three coating types: simple black paint, 2% TiO_2 nanopaint and 4% TiO_2 nanopaint. It has been noted that the distillate yield with the use of nanopaint coatings especially showed significant improvement in yields at higher concentrations, thereby proving the effectiveness of TiO_2 nanoparticles in increasing the operational efficiency of solar stills.

3.1 Timewise Measurement of Meteorological Parameters

The test was carried out over a 9-hour period, from 9 hr in the morning to 18 hr in the evening, and the meteorological parameters are shown in Fig. 5. During the morning hours, the intensity of solar radiation was highest in the eastern direction, as the maximum insolation was received from this orientation. Conversely, the intensity was lower in the western and southern directions at this time. As the day moved on, maximum insolation changed due to the movement of the Earth, as depicted in Fig. 6. The highest insolation flux occurred towards the south at 12:00 h; however, due to the single slope of the still, the productivity is also greater in this direction. In short-term thermal loads, the maximum insolation had shifted to the west, so that the slope solar with the double-slope was more efficient in this period. The highest insolation during the experiment was 906 W/m^2 at 11:00 AM on the eastern glass surface, which was 25% and 58% higher than the insolation received on the southern and western glass surfaces, respectively. Additionally, the maximum temperature on the western glass surface was recorded at 890 W/m² at 3:00 PM.

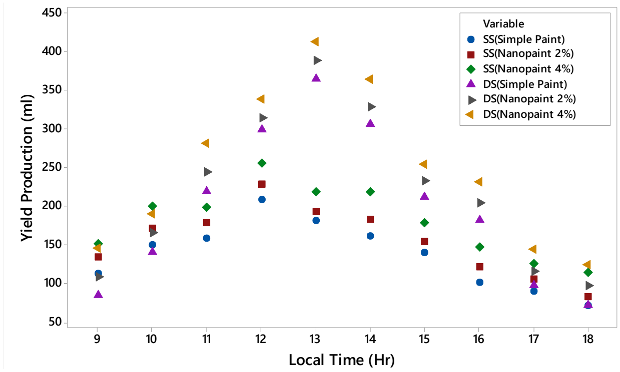


Fig. 5. Yield Production of simple solar still (SS) and Double Solar Still (DS) at 10 mm raw water depth (Month-March)

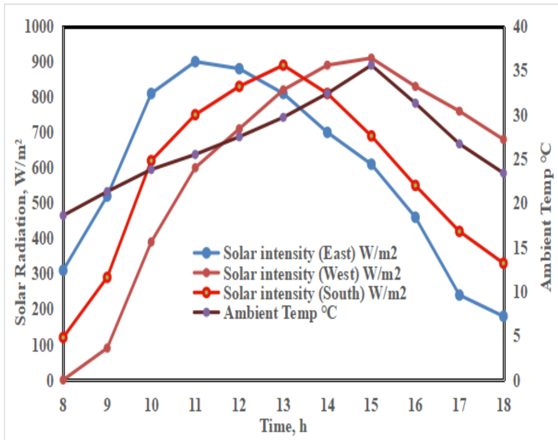


Fig. 6. The hourly measured intensity and atmospheric temperature

3.2 Effect of Coating Material on Yield for the Month of March

Nanopaint coatings led to a greater yield of distilled water over both months and all water depths. Fig. 5 shows the amount of fresh water produced each hour by single-slope (SS) and double-slope (DS) solar stills with different types of coatings: simple paint, 2% nanopaint, and 4% nanopaint at a 10mm water depth in March. The data was collected from 9:00 AM to 6:00 PM. The results clearly show that using nanopaint helps make the stills work better. The simple solar still with a 10 mm water depth yielded 1377 ml with simple paint, 1553 ml with 2% TiO_2 nanopaint, and 1811 ml with 4% TiO_2 nanopaint (Table 2). This is a relative improvement of around 12.77% and 31.5% for 2% and 4% concentration, respectively, when compared to simple paint. This shows that using more nanopaint helps the stills absorb and transfer heat more efficiently.

Similarly, the simple solar still with a 20 mm water depth yielded 1201 ml with simple paint, 1543 ml with 2% TiO_2 nanopaint, and 1650 ml with 4% TiO_2 nanopaint as shown in Fig. 7 and Table 2. Additionally, the still with 30 mm water depth yielded 1061 ml with simple paint, 1210 ml with 2% TiO_2 nanopaint, and 1525 ml with 4% TiO_2 nanopaint, as shown in Fig. 8 and Table 2. The upgraded thermal conductivity and solar absorption properties of the TiO_2 nanoparticles are indeed responsible for this specific enhancement. The thermal retention resulting from these nanoparticles leads to enhanced productivity due to faster evaporation of water from the basin. Further, the thermal efficiency is also improved due to the finer particle size, which increases the surface-to-volume ratio.

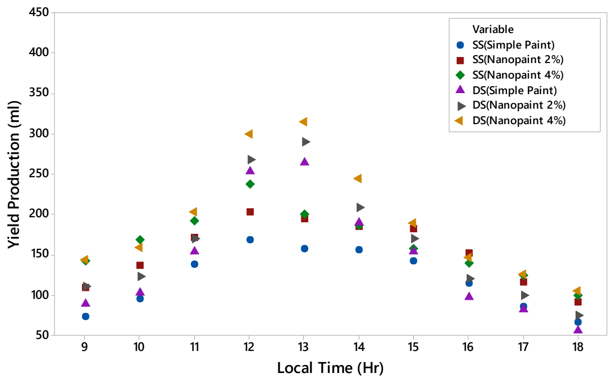


Fig. 7. Yield Production of simple solar still (SS) and Double Solar Still (DS) at 20 mm raw water depth (Month-March)

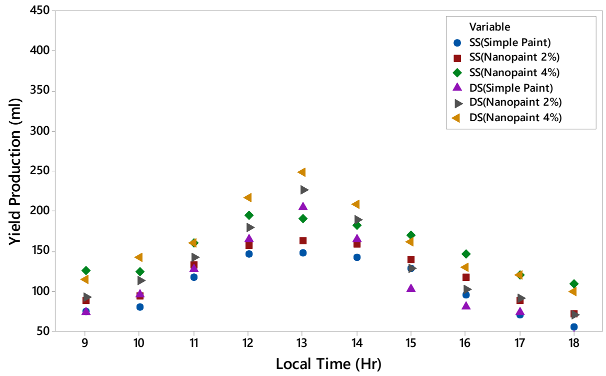


Fig. 8. Yield Production of simple solar still (SS) and Double Solar Still (DS) at 30 mm raw water depth (Month-March)

3.3 Effect of Coating Material on Yield for the Month of May

The Fig. 9 shows the amount of fresh water produced each hour by single slope (SS) and double slope (DS) solar stills with different types of coatings: simple paint, 2% nanopaint, and 4% nanopaint at 10mm water depth in May. The simple solar still with a 10 mm water depth yielded 1446 ml with simple paint, 1694 ml with 2% TiO_2 nanopaint, and 1910 ml with 4% TiO_2 nanopaint (Table 4). Similarly, the simple solar still with a 20 mm water depth yielded 1330 ml with simple paint, 1569 ml with 2% TiO_2 nanopaint, and 1746 ml with 4% TiO_2 nanopaint, as shown in Fig. 10 and Table 4. Additionally, the still with 30 mm water depth yielded 1156 ml with simple paint, 1372 ml with 2% TiO_2 nanopaint, and 1563 ml with 4% TiO_2 nanopaint as shown in Fig. 11 and Table 4.

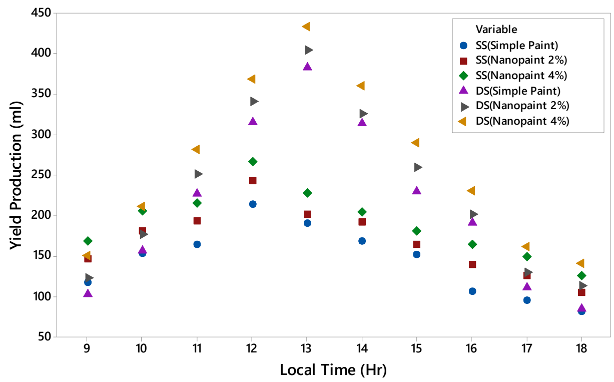


Fig. 9. Yield Production of simple solar still (SS) and Double Solar Still (DS) at 10 mm raw water depth (Month-May)

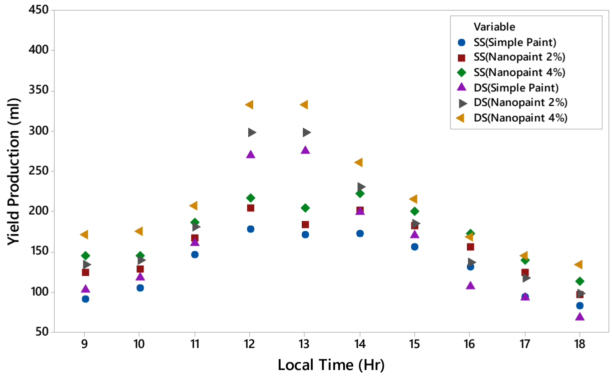


Fig. 10. Yield Production of simple solar still (SS) and Double Solar Still (DS) at 20 mm raw water depth (Month-May)

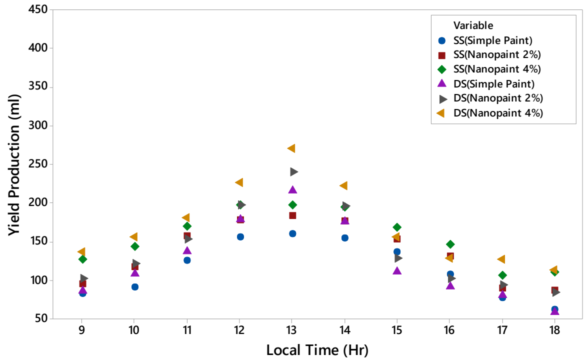


Fig. 11. Yield Production of simple solar still (SS) and Double Solar Still (DS) at 30 mm raw water depth (Month-May)

Table 2. Yield performance of the simple solar still for the month of March

Time	March-Simple-10 mm water			March-Simple-20 mm water			March-Simple-30 mm water		
	Simple Paint	Nanopaint 2%	Nanopaint 4%	Simple Paint	Nanopaint 2%	Nanopaint 4%	Simple Paint	Nanopaint 2%	Nanopaint 4%
9	113	134	152	73	109	142	75	88	126
10	150	171	200	96	137	169	81	94	124
11	159	178	199	138	172	192	118	133	161
12	208	229	255	169	203	237	146	157	195
13	182	193	218	158	195	201	148	163	191
14	162	183	219	156	185	187	143	159	182
15	140	155	179	143	182	158	128	139	170
16	102	121	148	115	152	140	96	117	147
17	90	106	126	86	116	124	71	88	120
18	71	83	115	67	92	100	55	72	109
Sum	**1377**	**1553**	**1811**	**1201**	**1543**	**1650**	**1061**	**1210**	**1525**

Table 3. Yield performance of the double solar still for the month of March

Time	March-Double-10 mm water			March-Double-20 mm water			March-Double-30 mm water		
	Simple Paint	Nanopaint 2%	Nanopaint 4%	Simple Paint	Nanopaint 2%	Nanopaint 4%	Simple Paint	Nanopaint 2%	Nanopaint 4%
9	84	109	146	88	110	144	74	93	115
10	140	166	190	103	123	159	96	114	142
11	218	244	282	154	170	203	127	142	161
12	298	314	339	253	268	299	165	180	217
13	364	389	413	264	290	315	204	226	249
14	305	328	364	189	208	245	164	189	208
15	211	233	254	154	170	189	103	129	162
16	182	205	232	97	120	147	81	103	130
17	97	116	144	82	100	126	74	92	121
18	71	97	124	56	75	105	45	70	100
Sum	**1970**	**2201**	**2488**	**1440**	**1634**	**1932**	**1133**	**1338**	**1605**

3.4 Simple vs. Double Slope Solar Stills

Across all water depths and both coating types, the total yield of the double slope solar still was greater than that of the simple slope still. In March, with 10 mm water and 4% TiO_2 nanopaint, the double slope still yielded 2488 ml (Table 3), and the simple still achieved 1811 ml (Table 2); this demonstrates a yield increase of 37.4%. This increase can be attributed to enhanced condensation integration alongside the dual-slope design, permitting the collection of condensate on both glass covers. This trend was also witnessed in May, where the double slope again demonstrated higher productivity. At 10 mm water depth and 4% TiO_2 nanopaint, the yield rose from 1910 ml (Table 4) in the simple still to 2628 ml (Table 5) in the double slope configuration. Enhanced ambient temperature and solar irradiance in May contributed to this additional yield relative to March.

3.5 Effect of Water Depth on Productivity

The depth of water in solar stills is of utmost importance as it determines productivity. Compared to the 20 mm and 30 mm water levels, the 10 mm water level consistently provided higher yields.

For instance, a solar still equipped with 4% TiO_2 nanopaint achieved yields of 1910 ml, 1746 ml, and 1563 ml for 10 mm, 20 mm, and 30 mm water column depths, respectively, during May (Table 4). The yield of distillate decreases with the increase in depth because the time a given quantity of water takes to heat in the shallow depth is comparatively less, leading to evaporation and a greater daily yield. The yield of distillate decreases with increasing depth because a shallower water column has a lower thermal mass and therefore requires less sensible heat input to reach the evaporation temperature. This faster heating leads to earlier onset of evaporation and longer effective operating hours for distillation throughout the day. In contrast, deeper water levels act as larger heat reservoirs, delaying temperature rise and reducing the basin water temperature gradient, which lowers the evaporation rate. Moreover, at lower depths, the enhanced heat transfer from the nanocoated basin surface to the water further accelerates evaporation, contributing to a greater daily yield.

Table 4. Yield performance of the simple solar still for the month of May

Time	May-Simple-10 mm water			May-Simple-20 mm water			May-Simple-30 mm water		
	Simple Paint	Nanopaint 2%	Nanopaint 4%	Simple Paint	Nanopaint 2%	Nanopaint 4%	Simple Paint	Nanopaint 2%	Nanopaint 4%
9	118	147	169	92	124	145	83	95	127
10	154	181	206	105	129	145	91	118	144
11	164	194	216	146	167	187	126	158	170
12	214	243	266	178	204	217	156	178	198
13	190	202	228	171	184	204	160	184	198
14	169	192	205	173	202	222	155	177	195
15	152	165	181	156	182	201	137	153	168
16	107	139	164	132	156	173	108	132	146
17	96	126	149	94	124	139	78	90	106
18	82	105	126	83	97	113	62	87	111
Sum	**1446**	**1694**	**1910**	**1330**	**1569**	**1746**	**1156**	**1372**	**1563**

Table 5. Yield performance of the double solar still for the month of May

Time	May-Double-10 mm water			May-Double-20 mm water			May-Double-30 mm water		
	Simple Paint	Nanopaint 2%	Nanopaint 4%	Simple Paint	Nanopaint 2%	Nanopaint 4%	Simple Paint	Nanopaint 2%	Nanopaint 4%
9	102	123	150	102	134	171	86	102	137
10	156	177	211	117	140	175	108	122	156
11	226	251	282	161	181	207	137	154	181
12	315	341	368	269	298	333	178	197	227
13	383	404	433	275	298	333	215	241	271
14	313	326	360	199	230	261	175	196	222
15	229	260	290	170	185	216	110	128	156
16	190	202	231	107	137	168	91	103	129
17	110	130	162	93	118	145	81	94	127
18	85	113	141	68	98	134	58	84	114
Sum	**2109**	**2327**	**2628**	**1561**	**1819**	**2143**	**1239**	**1421**	**1720**

3.6 Impact of Climatic Month on Performance

Productivity is also affected considerably by seasons. With no regard to the type of coating or the configuration of the still, the data indicates a tendency towards increased productivity in May relative to March. This increase is explained by higher May temperatures and more solar insolation, which increase the system's total energy input and quicken the evaporation-condensation process. For instance, the double-slope solar still with a 4% TiO_2 nanopaint coating and a 10 mm water depth produced 2488 ml in March (Table 3) and 2628 ml in May (Table 5), representing a 5.6% increase. Such seasonal improvement was observed across all experimental conditions, confirming the strong dependence of freshwater yield on solar radiation intensity and ambient temperature.

3.7 Optimal Conditions

Provided the data, the triangular solar still, along with the 4% TiO_2 nanopaint and 10 mm depth of water, yielded the maximum distillate in waters in both months. The highest yield recorded was 2628 ml in May with these conditions. This indicates that the efficiency of the solar distillation system is significantly increased by combining structural optimization (double slope), material innovation (nanopaint), and operational design (shallow water depth).

3.8 Nano Paint Effectiveness

The presence of TiO_2 nanoparticles increases heat conduction and solar energy absorption, which is primarily why stills coated with nanopaint perform better. The effect is stronger at 4% than at 2%, indicating that, at least initially, there may be a functional relationship between performance and nanoparticle concentration.

However, after a certain concentration, the concentration of nanoparticles may cause agglomeration of light scattering, which reduces the impact of the nanoparticles. However, this phenomenon was not observed within the study parameters. Moreover, SEM examination of the basin surfaces (Figs. 3 and 4 in the previous section) confirmed the durability and structural integrity of the nanopaint over a period of prolonged use. During the operation of a solar still for 20 days, the microstructural properties of the nanopaint were intact, whereas normal paint exhibited signs of deterioration. This resilience helps to maintain consistent thermal performance over time and confirms the soak time reliability of nanopaint in solar thermal systems.

3.9 Practical Implications

The findings of this study have a number of practical implications. For one thing, the formulation of nanopaint is highly beneficial to solar stills because it allows solar stills to be efficient in terms of cost by producing more yield each day without a massive jump in extra capital costs. However, double-slope solar stills that use nanopaint and maintain an optimum water level provide greater productivity benefits, despite having a more complex design. These results are especially helpful for deployment in remote areas where clean drinking water is an issue, but strong sunlight is widespread. However, on the other hand, double-slope solar stills with nanopaint and optimum water level offer greater productivity benefits, even though their design is more complex. Integrating nanotechnology into the conventional design of solar stills opens new avenues for combating water scarcity sustainably with low-maintenance technologies.

4 CONCLUSION

The current experimental study focused on the optimization of the thermal performance of single and double-slope solar stills by using TiO_2 nanoparticle-infused coatings during the real weather conditions between March and May. It was observed throughout the months that the application of TiO_2 nanoparticles enhanced the solar stills' evaporative and condensative behaviour more than control samples, which were coated with simple black paint. Out of all the configurations tested the 4% TiO_2 nanocoating showed the highest water yield at all depths and for both still types. The key findings are summarised as follows.

- Single-slope solar stills demonstrated significantly higher freshwater yields when coated with TiO_2 nanopaint compared to conventional painted surfaces.
- In March, the 4% TiO_2 nanocoating at a 10 mm water depth achieved the maximum yield of 1811 ml/m², representing a clear improvement over the 1377 ml/m² obtained with simple paint. This performance further improved in May, where the 4% nanocoated layer, still at the same water depth, reached 1910 ml/m².

- All conditions were met with the double slope stills as they outperformed single slope stills. The double slope stills had better thermal management as well as a greater condensation surface area with the 4% TiO_2 nanocoating, yielding 2488 ml/m^2 in the month of March, then achieving 2628 ml/m^2 in the same month.
- In both cases, a claim of 10mm resulted in higher productivity when compared with 20mm and 30mm. The enhanced productivity was due to the reduction in water volume that required heating.
- Compared to March, the heightened external temperatures and boosted solar radiation in May helped improve still performance, confirming the design effectiveness under different climatic test conditions.
- Across all depths and still types, the impact of the nanocoating was noticeable. With the application of the nanocoating, the stills were able to absorb more solar radiation, while at the same time, reducing thermal losses and providing more efficient cooling basin water, which led to more evaporation.
- In the experimentation, the use of TiO_2 was found to be very effective for solar distillation. In the experimentation, the use of TiO_2 was found to be very effective for solar distillation. With the use of a 4% TiO_2 coating, the freshwater yield was significantly improved.
- Also, further work should focus on better dispersion and adhesion methods for nanoparticle coatings to achieve long-term structural integrity and good thermal functionality under harsh operating conditions.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

REFERENCES

[1] H. Panchal, K.K. Sadasivuni, Experimental investigation on solar still with nanomaterial and dripping arrangement. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects,* 47(1), 2025:1886–1896. https://doi.org/10.1080/15567036.2020.1834647

[2] A.H. Abed, H.A. Hoshi, M.H. Jabal, Experimental investigation of modified solar still coupled with high-frequency ultrasonic vaporizer and phase change material capsules. *Case Studies in Thermal Engineering*, 28, 2021: 101531. https://doi.org/10.1016/j.csite.2021.101531

[3] G. Murali, P. Ramani, M. Murugan, P.V. Elumalai, N.U. Ranjan Goud, S. Prabhakar, Improved solar still productivity using PCM and nano-PCM composites integrated energy storage. *Scientific Reports*, 14, 2024: 15609. https://doi.org/10.1038/s41598-024-65418-1

[4] M.Abdelgaied, Y.Zakaria, A.E. Kabeel, F.A. Essa, Improving the tubular solar still performance using square and circular hollow fins with phase change materials. *Journal of Energy Storage*, 38, 2021: 102564. https://doi.org/10.1016/j.est.2021.102564

[5] A.E. Kabeel, R. Sathyamurthy, A.M. Manokar, S.W. Sharshir, F.A. Essa, A.H. Elshiekh, Experimental study on tubular solar still using Graphene Oxide Nanoparticles in Phase Change Material (NPCM's) for fresh water production. Journal of Energy Storage, 28, 2020: 101204. https://doi.org/10.1016/j.est.2020.101204

[6] V.V. Tyagi, S.K.Pathak, K. Chopra, A. Saxena, A. Dwivedi, V. Goel, R.K. Sharma, R. Agrawal, A.A. Kandil, M.M. Awad, R. Kothari, A.K. Pandey, Sustainable growth of solar drying technologies: Advancing the use of thermal energy storage for domestic and industrial applications. *Journal of Energy Storage,* 99(Part B), 2024: 113320. https://doi.org/10.1016/j.est.2024.113320

[7] M.R. Hajizadeh, F. Selimefendigil, T. Muhammad, M. Ramzan, H. Babazadeh, Z. Li, Solidification of PCM with nano powders inside a heat exchanger. *Journal of Molecular Liquids*, 306, 2020: 112892. https://doi.org/10.1016/j.molliq.2020.112892

[8] M. Jurčević, S. Nižetić, M. Arıcı, H.A. Tuan, E. Giama, A. Papadopoulos, Thermal constant analysis of phase change nanocomposites and discussion on selection strategies with respect to economic constraints. *Sustainable Energy Technologies and Assessments*, 43, 2021: 100957. https://doi.org/10.1016/j.seta.2020.100957

[9] A.E. Kabeel, Z.M. Omara, F.A. Essa, Numerical investigation of modified solar still using nanofluids and external condenser. *Journal of the Taiwan Institute of Chemical Engineers*, 75, 2017: 77–86. https://doi.org/10.1016/j.jtice.2017.01.017

[10] M.A. Alazwari, M. Algarni, M.R. Safaei, Effects of various types of nanomaterials on PCM

melting process in a thermal energy storage system for solar cooling application using CFD and MCMC methods. *International Journal of Heat and Mass Transfer*, 195, 2022: 123204. https://doi.org/10.1016/j.ijheatmasstransfer.2022.123204

[11] M. Alktranee, Q. Al-Yasiri, K.S. Mohammed, M. Arıcı, M. Szabó, P. Bencs, Energy, exergy, and economic analysis of indirect solar dryer integrated phase change material cans. *Energy Conversion and Management: X, 26,* 2025: 100986. https://doi.org/10.1016/j.ecmx.2025.100986

[12] S.M. Abzal, J.K. Dash, C. Mahata, A. Guchhait, A. Kumar, S. Ramakrishna, G.K. Dalapati, Improvement of p-CuO/n-Si heterojunction solar cell performance through nitrogen plasma treatment. *Journal of Electronic Materials*, 50(4), 202: 1720–1725. https://doi.org/10.1007/s11664-020-08593-x

[13] R. Agrawal, R.K. Sharma, K. Sharma, M.I.H. Siddiqui, Thermophysical characterization and chemical stability of Ag_2O-enhanced eutectic nano-PCMs for moderate-temperature applications. *International Journal of Chemical Reactor Engineering.* Advance online publication, 2025. https://doi.org/10.1515/ijcre-2025-0081

[14] D.H.A. Besisa, E.M.M. Ewais, Y.M.Z. Ahmed, A comparative study of thermal conductivity and thermal emissivity of high temperature solar absorber of ZrO_2/Fe_2O_3 and Al_2O_3/CuO ceramics. *Ceramics International*, 47(20), 28252–28259. https://doi.org/10.1016/j.ceramint.2021.06.240

[15] K. Gaur, S. Chauhan, Ajit, G. Kajal, Productivity analysis of pyramid solar still using phase change material and hybrid nanofluid. *Lecture Notes in Mechanical Engineering*, 2022: 621–634. https://doi.org/10.1007/978-981-99-1894-2_53

[16] T. Egli, J. Bolluger, F. Kienast, Evaluating ecosystem service trade-offs with wind electricity production in Switzerland. *Renewable and Sustainable Energy Reviews*, 67, 2017: 1308–1330. https://doi.org/10.1016/j.rser.2016.09.074

[17] M.M. Ali Saeed, D.M. Hachim, H.G. Hameed, Numerical investigation for single slope solar still performance with optimal amount of Nano-PCM. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, 63(2), 2024: 302–316

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

[19] P. Dumka, Y. Kushwah, A. Sharma, D.R. Mishra, Comparative analysis and experimental evaluation of single slope solar still augmented with permanent magnets and conventional solar still. *Desalination,* 459, 2019: 34–45. https://doi.org/10.1016/j.desal.2019.02.012

[20] A.E. Kabeel, R. Sathyamurthy, S.W. Sharshir, A. Muthumanokar, H. Panchal, N. Prakash, C. Prasad, S. Nandakumar, M.S. El Kady, Effect of water depth on a novel absorber plate of pyramid solar still coated with TiO_2 nano black paint. *Journal of Cleaner Production,* 213, 2019: 185–191. https://doi.org/10.1016/j.jclepro.2018.12.185

[21] J. Kateshia, V.J. Lakhera, Analysis of solar still integrated with phase change material and pin fins as absorbing material. *Journal of Energy Storage,* 35, 2021: 102292. https://doi.org/10.1016/j.est.2021.102292

[22] M. Arici, E. Tutuncu, A. Campo, Numerical investigation of melting of paraffin wax dispersed with CuO nanoparticles inside a square enclosure. *Heat Transfer Research*, 49(9), 2018: 847–863. https://doi.org/10.1615/HeatTransRes.2018019748

[23] N.A. Pambudi, I.R. Nanda, A.D. Saputro, The energy efficiency of a modified v-corrugated zinc collector on the performance of solar water heater (SWH). *Results Engineering*, 18 2023: 101174. https://doi.org/10.1016/j.rineng.2023.101174

[24] L.O. Afolabi, C.C. Enweremadu, M.W. Kareem, A.I. Arogundade, K. Irshad, S. Islam, K.O. Oladosu, A.M. Elfaghi, D.H. Didane, Experimental investigation of double slope solar still integrated with PCM nanoadditives microencapsulated thermal energy storage. *Desalination*, 553, 2023: 116477. https://doi.org/10.1016/j.desal.2023.116477

[25] W. Hamali, M.Y. Almusawa, Transient heat transfer of NEPCM during solidification using Galerkin method. *Case Studies in Thermal Engineering*, 35, 2021: 102114. https://doi.org/10.1016/j.csite.2022.102114

[26] K. Ganesan, D.P. Winston, S. Ravishankar, S. Muthusamy, Investigational study on improving the yield from hybrid PV/T modified conventional solar still with enhanced evaporation and condensation technique—An experimental approach. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 44(2), 2022: 5267–5286. https://doi.org/10.1080/15567036.2022.2083273