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Productivity enhancement of a Double Slope Solar Still Utilizing Nano-enhanced Phase Change Material

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ABSTRACT

The influence of phase change material (PCM) mixed with nanoparticles at different concentrations (1%, 3%, and 5%) on the performance of a double-slope solar still has been explored experimentally in this work. The experimental apparatus is a basin-type solar still with magnesium heptahydrate as the PCM, impregnated with copper powder nanomaterial encapsulated in aluminium tubes located beneath the absorber plate. The experiments have been conducted in outdoor conditions from 10:00 to 17:00 hours with measurements recorded every hour for solar radiation, glass cover temperature, absorber plate temperature, basin water temperature, and distilled water output. Solar radiation is highest between 12:00 and 13:00 hours, which results in peak absorber plate and basin water temperatures. Without nano-enhanced PCM, extreme fluctuations in component temperatures are observed, whereas integrating PCM smoothes these oscillations by storing excess heat during peak times and releasing it subsequently. The heat-absorbing capacity of nano-enhanced PCM results in improved distilled water output. Among the cases tested, the PCM - 5% copper nanoparticle-based system yields the maximum of 750 ml, which is 48.5% more than the 505 ml yield of the conventional system. Increasing the nanoparticle concentration increases yield each time, especially at high solar intensity. The results reveal that PCM and nanoparticle hybridisation enhances thermal stability, latent heat storage capacity and remarkably increases freshwater yield, thus rendering the system efficient, stable, and viable for high diurnal temperature fluctuation.

Keywords: *Solar still, Phase Change Material, Nano-particles, Thermal regulation, Distilled water yield.*

1. Introduction

Solar distillation is an eco-friendly and renewable method of generating drinking water using solar energy with the help of evaporation and condensation processes. Its ease of operation, low price tag and effectiveness in replicating the natural hydrological cycle render it extremely well-suited to solve freshwater shortage issues in arid and semi-arid climates. Solar stills are divided into three categories: passive, active, and hybrid designs. Passive stills, for example, single-basin, double-basin, tilted, and wick-type systems, depend only on solar radiation and are appropriate for small-scale applications, while active stills use auxiliary sources of energy, such as multi-effect, membrane and vacuum distillation types, to increase thermal efficiency. Hybrid designs further enhance the reliability of the systems by integrating the solar energy with auxiliary heating, allowing the systems to operate continuously under varying weather conditions [1,2].

Of these systems, the double-slope solar still (DSSS) has been of great interest because of improved performance over single-slope designs. The dual slope covers enhance surface area for condensation thereby improving daily freshwater production and thermal efficiency. It is reported that DSSSs produce average efficiencies of 36% as opposed to 31% by pyramidal top covers, with a productivity level of 1350 ml/m²/day compared to 1200 ml/m²/day for single-slope arrangements [3]. In addition, the capability of DSSSs to trace solar radiation from arbitrary angles guarantees enhanced efficiency at early morning and late afternoon hours. All these benefits, together with easy construction, place DSSSs in particular as very suitable for high solar potential areas like Pantnagar (Uttarakhand) India, which can receive 4–6 kWh/m^2/day solar radiation with optimal conditions for applications of solar desalination.

Recent research reveals that combination of nano-particles and phase change materials (PCMs) are efficient means to augment performance of DSSS. The nano-particles increase thermal conductivity, speed up evaporation efficiency and enhance freshwater output by 30% in comparison with traditional designs [4]. Design improvements, such as reflective surfaces, step-wise basins, and sun-trackers, have also improved thermal efficiency by over 300% [5]. Concurrently, PCMs like paraffin wax and magnesium sulphate heptahydrate ($Mg_2SO_4 \cdot 7H_2O$) retain surplus solar heat during sunny hours and give it out during cooler hours, continuing distillation beyond sunshine hours. Paraffin wax enhances passive still yield by 180% and active stills by 300%, whereas $Mg_2SO_4 \cdot 7H_2O$ elevates freshwater production from 1400 ml/m^2/day to 1960 ml/m^2/day, while corresponding efficiency increases from 47% to 64% [6,7].

Following the developments in desalination technologies, the present work is concerned with the experimental performance assessment of a double-slope solar still integrated with magnesium sulphate heptahydrate as PCM and copper nano-particles mixture during winter months in Pantnagar, India. The effect of water depth on system performance and thermal behaviour has been analysed while focussing on the effectiveness of PCM integration with nano-particles to enhance freshwater production. Hence, the present work supports the design and development of affordable and sustainable desalination technologies for water-scarce areas.

2. Research Methodology

The double-slope solar still has been fabricated from locally available, low-cost materials to ensure practical applicability. A treated plywood frame (1.0×0.6×0.15 m^3) provided structural support, while the basin was lined with black-painted aluminium to maximize solar absorption. Two transparent glass covers (5 mm thick, 29° inclination) were fixed on both sides to allow radiation entry and enhance condensation, with silicone sealing applied to prevent vapor leakage. A PVC channel at the cover lowest point collected condensate into graduated flasks. Magnesium sulphate heptahydrate ($MgSO_4 \cdot 7H_2O$) was encapsulated in aluminium containers and placed in the basin to serve as a phase change material (PCM), storing latent heat during peak hours and releasing it later. Glass wool insulation (0.05 m) was provided around the basin to minimize heat losses.

Thermal and performance parameters have been continuously monitored using calibrated instruments. Type-K thermocouples are placed at the absorber plate, basin water, PCM, and glass covers, connected to a microprocessor-based data logger for automated recording. Mercury thermometers are used for calibration. A pyranometer is used to measure solar irradiance. Distillate yield is collected in 500 ml graduated flasks from both slopes to enable comparative evaluation. Magnesium sulphate heptahydrate is selected as the PCM due to its high latent heat, distinct melting point, cost-effectiveness, and non-toxic nature. Its encapsulation in aluminium containers ensured stability during repeated melting–solidification cycles. To enhance conductivity, copper nano-particles are incorporated in varying proportions (0–5% by weight). This integration is expected to improve thermal response and extend distillation beyond sunshine hours. Fig. 1 shows the heat transfer mechanism of solar still.

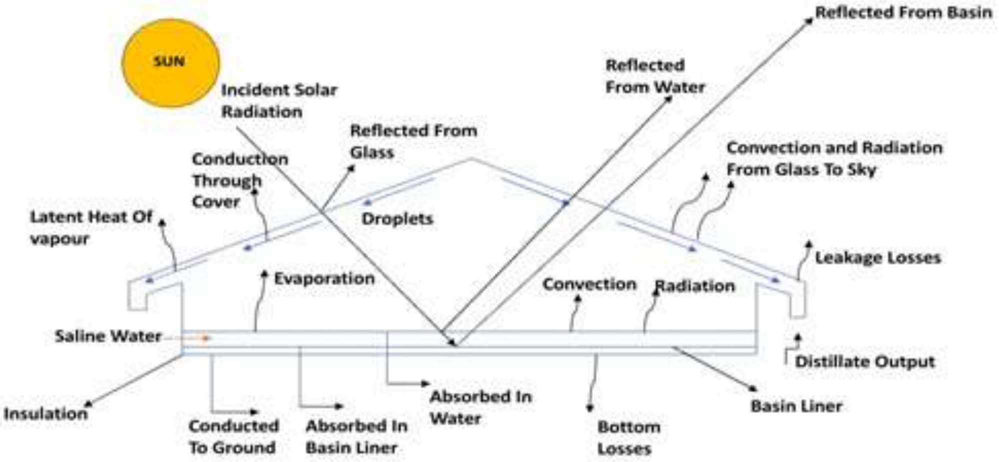

Figure 1: Heat transfer Mechanism of Solar Still

The system is installed in Pantnagar (29.02°N, 79.49°E), India, with orientation along the north–south axis for maximum solar exposure. Experiments are performed between 10:00 AM and 5:00 PM under real climatic conditions. A saline solution of 10 % concentration (prepared by dissolving 1 kg of salt in 10 litre of water) is maintained at a depth of 20–30 mm. Two configurations are tested: (i) without PCM and (ii) with PCM-nano particles integration. Hourly data for water and PCM temperature, absorber and cover temperatures, ambient conditions, and distillate yield are recorded. Precautions included ensuring airtight sealing, maintaining uniform water depth, and cleaning glass covers before each trial. At the end of each day, residual brine is drained and the basin is cleaned before the next run.

2.1. Economic Analysis

Economic analysis in solar desalination assesses the cost-effectiveness and financial viability of the system over its lifespan. The cost per litre of distilled water is a critical indicator, providing insight into the system’s competitiveness compared to conventional purification methods [8,9]. The performance can further be evaluated using energetic and exergetic cost ratios, expressed as:

$$R_{\boldsymbol{Ex}} = \frac{Ex_{out,ann}}{TAC} \tag{1}$$

$$R_{\boldsymbol{En}} = \frac{En_{out,ann}}{TAC} \tag{2}$$

where TAC is the total annual cost ($), defined as:

$$TAC = FAC + AMC - ASV \tag{3}$$

The first annual cost (FAC) is calculated as:

$$FAC = C_c \times CRF \tag{4}$$

with the capital recovery factor (CRF) given by:

$$CRF(i,n) = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{5}$$

The annual salvage value (ASV) is estimated from:

$$ASV = S \times SFF \tag{6}$$

$$SFF = \frac{i}{(1+i)^n - 1} \tag{7}$$

Here, C_c is the capital cost, AMC is the annual maintenance cost, S is the salvage value, iii is the interest rate, and n is the system lifetime. The annual energy output $En_{out,ann}$ corresponds to the total useful heat gained, while the annual exergy output $Ex_{out,ann}$ quantifies the fraction convertible into useful work. Thus, $R_{\boldsymbol{En}}$ and $R_{\boldsymbol{Ex}}$ provide direct measures of the system's cost-effectiveness in terms of energy and exergy utilization [9,10].

3. Results and Discussion

The performance of the double-slope solar still (DSSS) (i) without PCM (conventional system) (ii) with PCM and (iii) with PCM-nanoparticles mixture has been evaluated experimentally under identical climatic conditions. The analysis includes several parameters, viz., solar radiation intensity, component temperature profiles, distillate yield and economic feasibility.

3.1. Temperature profiles of DSSS with and without PCM

The performance of system in terms of temperature profiles of components and has been presented in the following subsections:

3.1.1 Temperature variation of DSSS without PCM

Figure 2 shows the diurnal variation of upper glass, absorber plate and basin water temperatures for the DSSS without PCM. The absorber plate consistently records the highest temperature throughout the day, reaching a maximum of 63.2 °C at 1 :00 PM due to its direct exposure to solar radiation and high absorptivity. The basin water temperature follows a similar pattern but remains comparatively lower, peaking at 54.8 °C at 2:00 PM because of the thermal lag associated with water's high specific heat capacity. The upper glass temperature remains the lowest, with a peak of 56.5 °C at 1 :00 PM as it looses heat to the ambient through convection and radiation. After mid day, all component temperatures gradually decline in response to decreasing solar radiation. The absorber plate retains heat longer than the other components, highlighting its critical role in sustaining the evaporation process even as solar intensity declines.

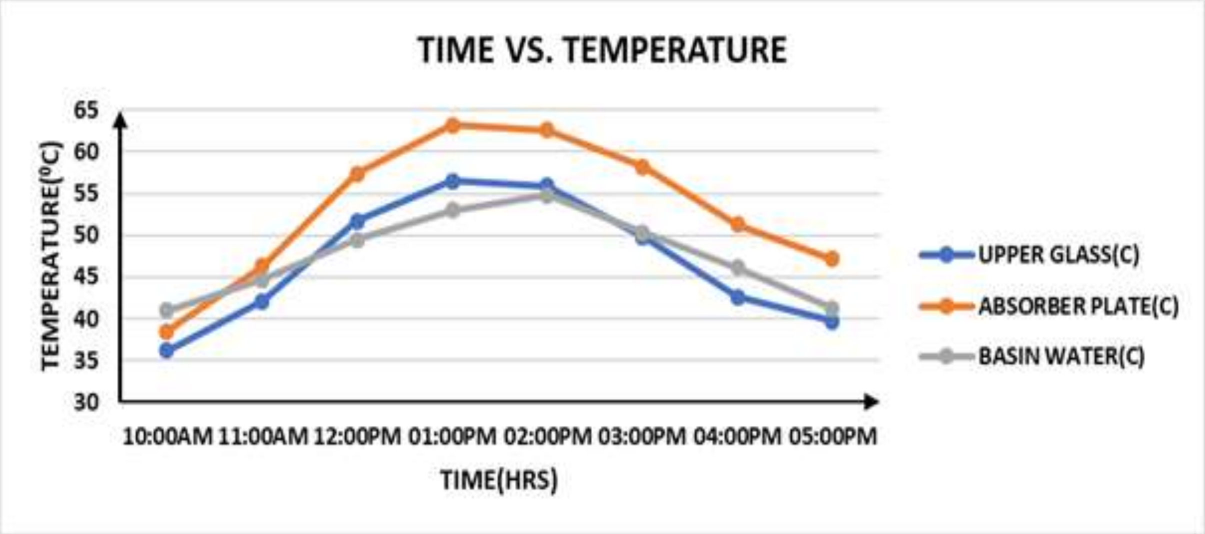

Figure2 : Temperature variation with time of the day of conventional DSSS

3.1.2 Temperature variation of DSSS with PCM

Figure 3 illustrates the temperature profiles of the upper glass, absorber plate, basin water, and PCM when inorganic phase change material, $MgSO_4{\cdot}7H_2O$ is used. Similar to the non-PCM case, the absorber plate attains the highest temperature, peaking at 53.95 °C around 1:00 PM. The basin water reaches a maximum of 50.93 °C at the same time, which is slightly lower than in the conventional still due to heat transfer into the PCM. The PCM temperature rises gradually during the day, attaining nearly 52.74 °C at 2:00 PM, corresponding to its phase transition range. This indicates that part of the absorbed solar energy is stored as latent heat rather than immediately contributing to basin water temperature rise. Notably, after 2:00 PM, while the absorber plate and basin water temperatures begin to decline, the PCM releases stored energy, which slows down the cooling rate of the system. The upper glass temperature remains lower compared to the other components, showing typical diurnal cooling trends. This behaviour confirms that PCM integration stabilizes thermal conditions and sustains evaporation for longer durations, thereby enhancing system performance beyond sunshine hours.

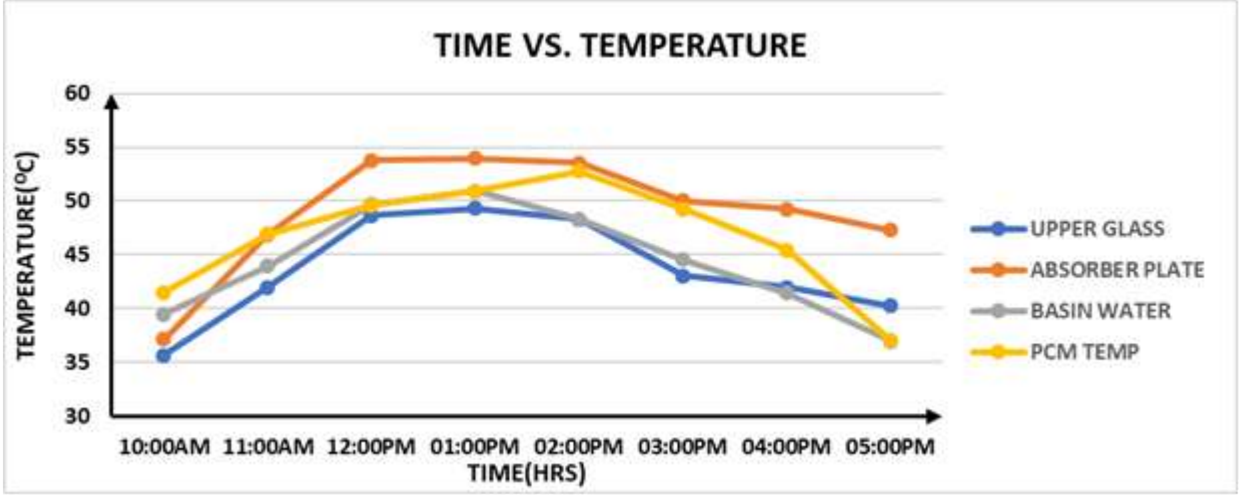

Figure 3: Temperature variation with time of the day of DSSS with PCM

3.2 Temperature variation of DSSS without PCM and with PCM - 1% nano-particles

The performance of system in terms of temperature profiles of components has been presented and discussed below:

3.2.1 Temperature variation of conventional DSSS

Figure 4 shows the hourly temperature variation of the upper glass, absorber plate and basin water in the conventional solar still without PCM and nanoparticles. The temperatures rise steadily from morning, reaching their maximum around 1:00 PM when solar radiation is at its peak. Among the components, the absorber plate consistently records the highest values due to direct solar exposure, while the basin water responds more slowly because of its larger thermal capacity. After midday, all temperatures gradually decline with the reduction in solar intensity, showing faster cooling compared to PCM-integrated systems. The absence of a thermal storage medium results in limited retention of absorbed heat, leading to shorter periods of effective distillation.

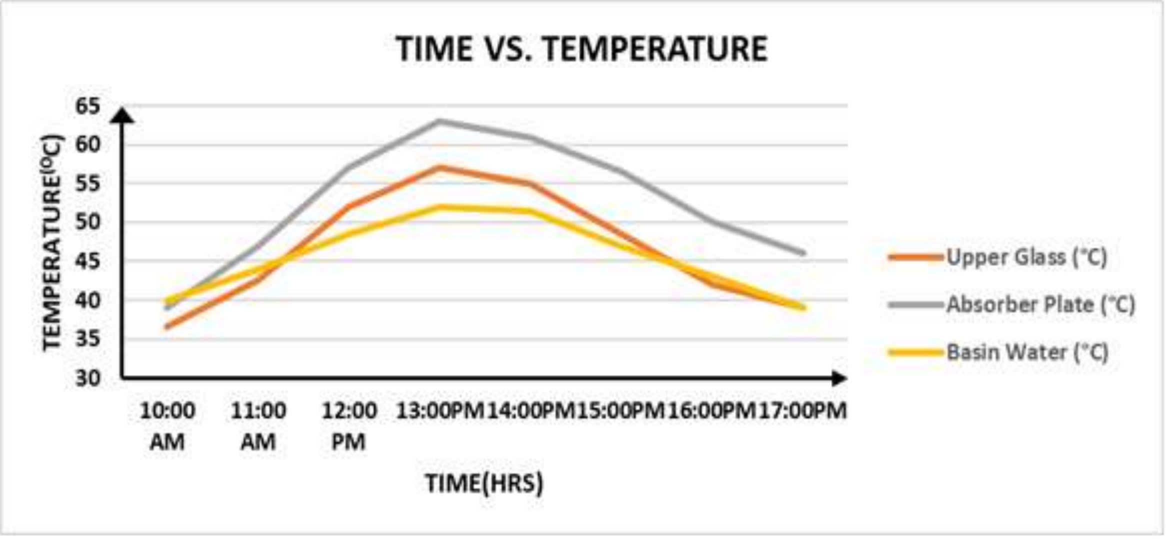

Figure 4 : Temperature variation with time of the day of conventional DSSS

3.2.2 Temperature variation of DSSS with PCM

Figure 5 presents the temperature variation when PCM enhanced with 1% nanoparticles is incorporated into the system. The integration of nanoparticles improves the thermal conductivity of the PCM, enabling rapid heat absorption during peak radiation hours and gradual release during the afternoon. The absorber plate reaches a maximum of 57.5 °C around 1:00–2:00 PM, while the PCM stabilizes near 55 °C, indicating active phase change and effective energy storage. Compared to the system without PCM, the afternoon temperatures remain significantly higher, which demonstrates the ability of the PCM–nano-particle mixture to extend the heating cycle. This extended thermal stability supports longer distillation hours and enhances freshwater yield, validating the role of nano-particles in improving PCM-assisted solar still performance.

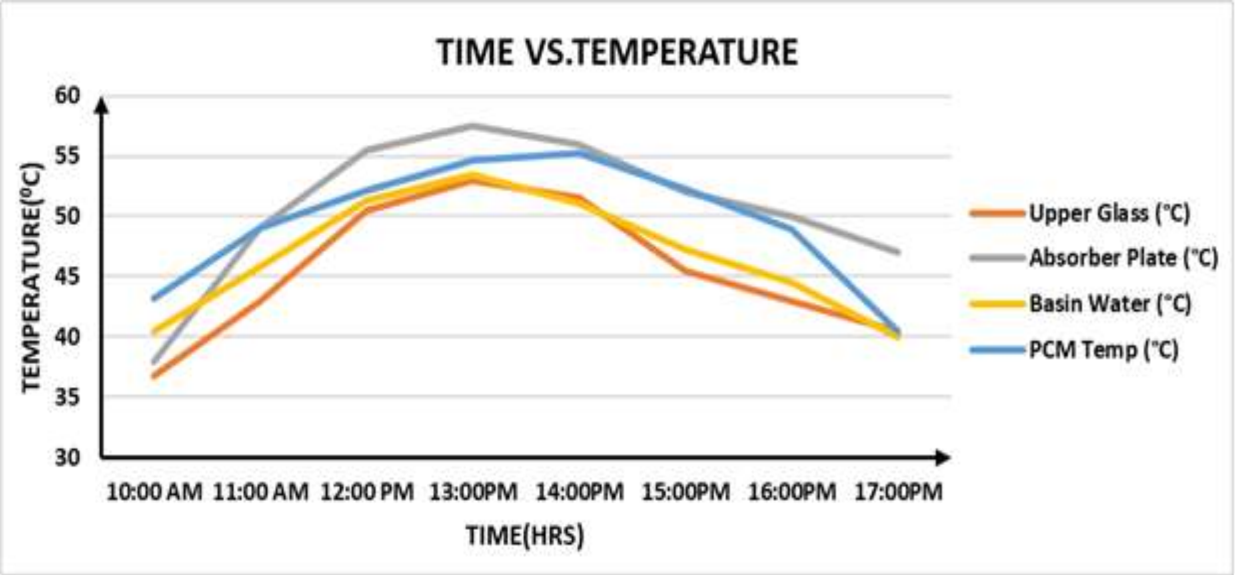

Figure 5: Temperature variation with time of the day of DSSS with PCM and 1% nano-particles

3.3 Temperature variation of DSSS without PCM and with PCM - 3% nano-particles

The performance of system in terms of temperature profiles of components of DSSS without PCM and with PCM - 3% nano-particles has been presented in this section.

3.3.1 Temperature variation of DSSS without PCM

Figure 6 show that the absorber plate consistently exhibited the highest temperature due to its direct exposure to solar radiation, reaching a maximum of 62.5 °C at around 1:00 PM. The basin water temperature followed a slower heating trend, attaining 52.5 °C, while the upper glass surface peaked at 56 °C during the same period. After midday, all components showed a gradual decline in temperature as solar intensity decreased. The basin water retained heat slightly longer than the glass due to its higher thermal capacity, but the overall system experienced rapid cooling in the absence of thermal storage.

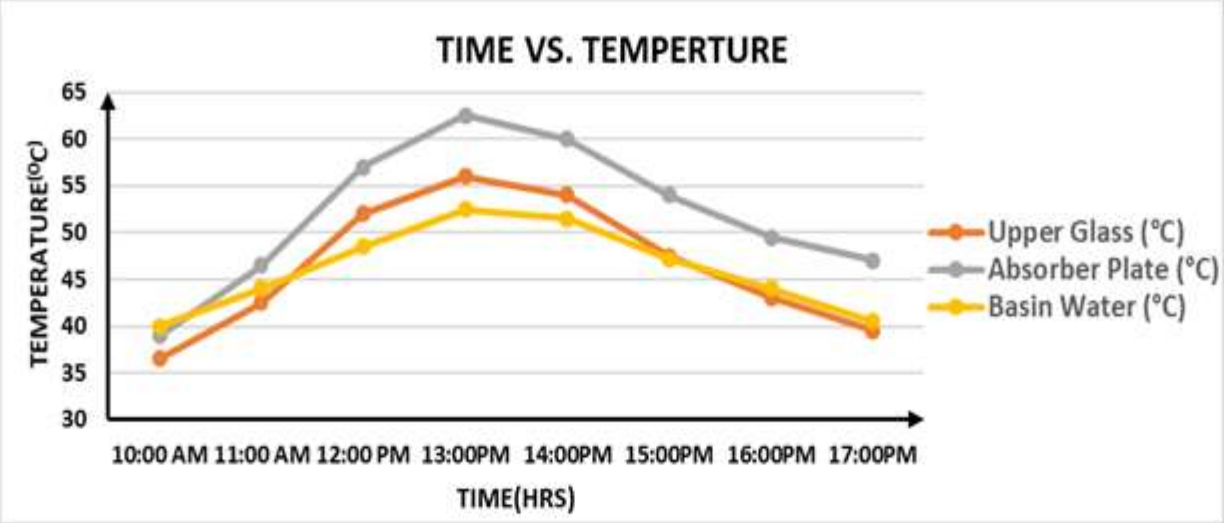

Figure 6: Temperature variation with time of the day of DSSS without PCM

3.3.2 Temperature variation with PCM - 3% copper nano-particles

By contrast, with PCM and 3% copper nano-particles the system demonstrated superior thermal performance as shown in Figure 7. During peak hours (12:00–2:00 PM), the absorber plate reached 62.8 °C and basin water rose to 55 °C, both higher than in the non-PCM case. The PCM temperature steadily increased throughout the day, rising from 24 °C at 10:00 AM to 65 °C by 3:00 PM, clearly indicating effective latent heat storage. Even as solar radiation declined after 2:00 PM, the PCM continued to release stored energy, thereby sustaining higher temperatures in the absorber plate and basin water compared to the non-PCM configuration. This delayed cooling effect highlights the ability of PCM with nanoparticles to buffer thermal fluctuations and extend system operation into evening hours.

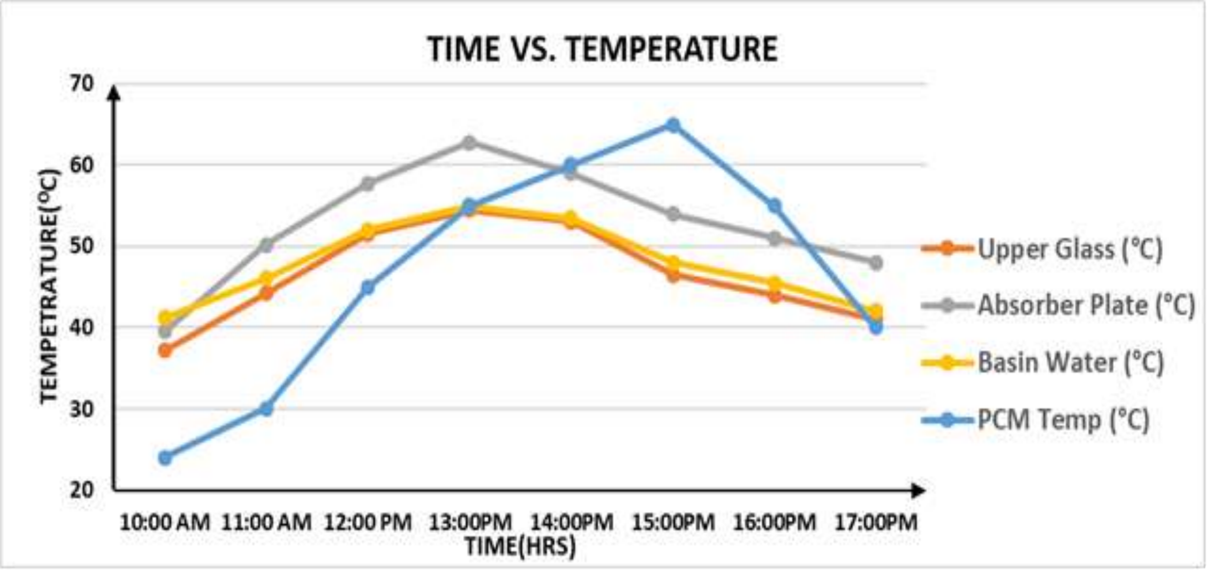

Figure7: Temperature variation with time of the day of DSSS with PCM and 3% nano-particles

3.4 Temperature variation of DSSS without PCM and with PCM-5% nano-particles

The temperature profiles of components of DSSS without PCM and with PCM-5% nano-particles have been presented in this section.

3.4.1 Temperature variation of DSSS without PCM

The thermal behavior of the solar still without PCM but with 5% nanoparticles is illustrated in Figure 8. All components show a steady rise in temperature during the morning, reaching maximum values around 1:00 PM. At this point, the absorber plate recorded 60.5 °C, while the basin water reached 54.5 °C. The upper glass surface also followed a similar trend, peaking near midday. However, as solar intensity declined in the afternoon, the temperatures of all components dropped rapidly, reflecting the absence of any thermal storage medium. This rapid cooling reduces the system's operational efficiency and restricts water production during the late afternoon hours.

3.4.2 Temperature variation of DSSS with PCM-5% nano-particles

When PCM enhanced with 5% copper nanoparticles was incorporated, the system shows markedly different behavior as shown in Figure 9. The absorber plate reached 63 °C and basin water peaked at 56 °C around 1:00 PM, while the PCM temperature continued to rise even beyond the solar peak, reaching 65 °C at 3:00 PM. This indicates active phase change and effective latent heat storage. Even as solar intensity reduced later in the day, the PCM gradually released stored heat, maintaining higher component temperatures. By 5:00 PM, the PCM still retained 50 °C, whereas the absorber plate, basin water, and glass also remained warmer compared to the non-PCM case.

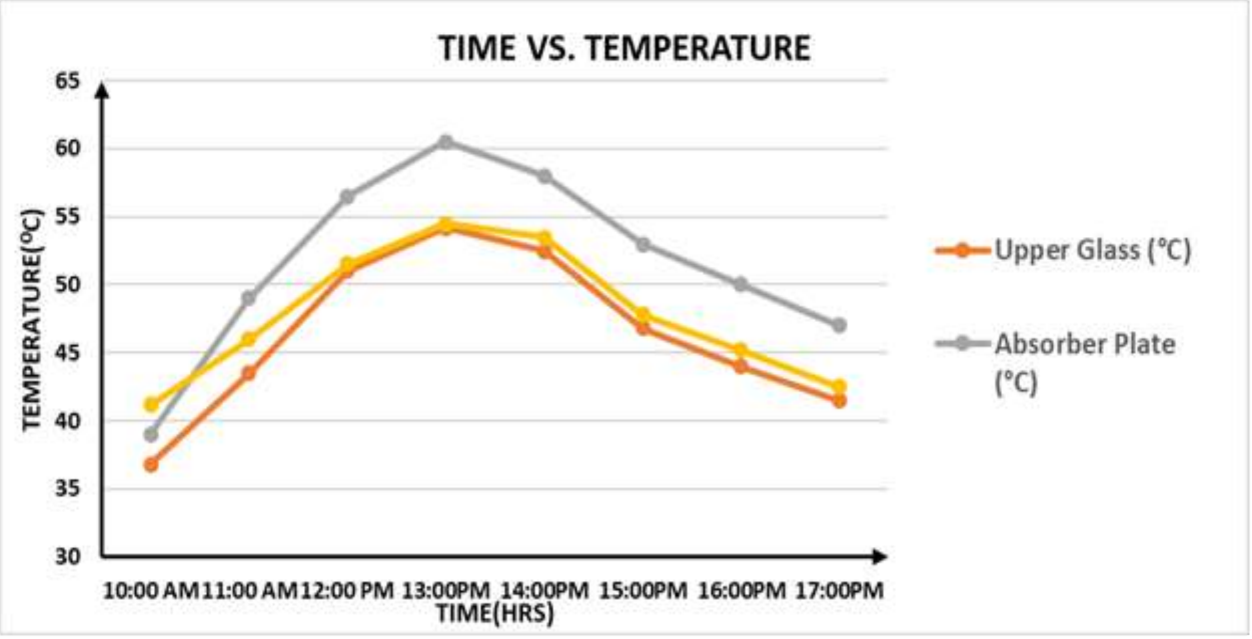

Figure 8: Temperature variation with time of the day of DSSS without PCM

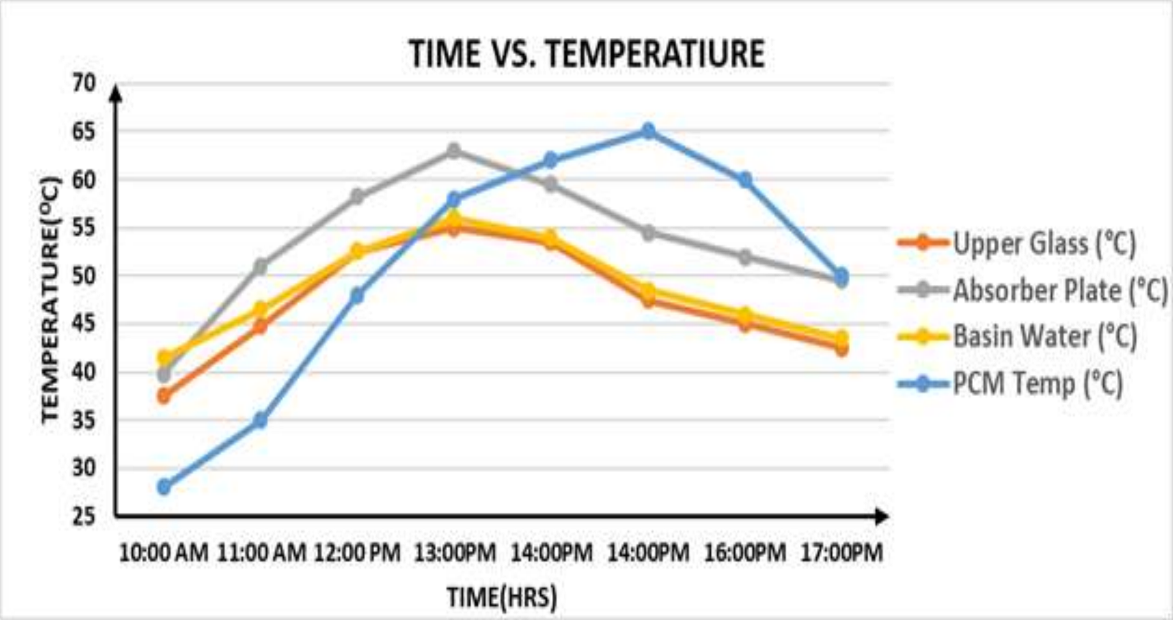

Figure 9: Temperature variation with time of the day of DSSS with PCM and 5% nano-particles

3.5 Fresh Water Productivity

The comparison of fresh water productivity of different DSSS i.e. conventional, with PCM and with different concentrations of nano-particles in PCM has been shown in Figure 10. Across all cases, the productivity is measured after 12:00 PM as the basin water reaches sufficient evaporation temperature. In the non-PCM cases, the yield rises until 1:00–2:00 PM, after which it drops sharply due to the lack of thermal storage. For example, for the conventional system produces a total of 355 ml, whereas the PCM-integrated system yielded 450 ml. With nano-particle-enhanced PCM, the performance improved substantially. At 1%

concentration of nano-particles in PCM, total yield reaches 520 ml as compared to 370 ml of conventional system. At 3% concentration, the yield jumped from 450 ml to 700 ml, showing the strong effect of PCM's latent heat storage combined with nano-particle conductivity enhancement. The best performance is recorded at 5% concentration, where productivity increased from 505 ml (without PCM) to 750 ml. This indicates that copper nano-particles significantly enhance the heat transfer rate within PCM, allowing faster charging during peak hours and slower discharge in the evening as shown in Figure 10.

Overall, the inclusion of PCM and nanoparticles extends the operational period of the still by maintaining higher basin water and glass cover temperatures during late afternoon hours. These results in delayed cooling, prolonged evaporation-condensation cycles and substantially higher cumulative fresh water yield compared to the baseline configuration.

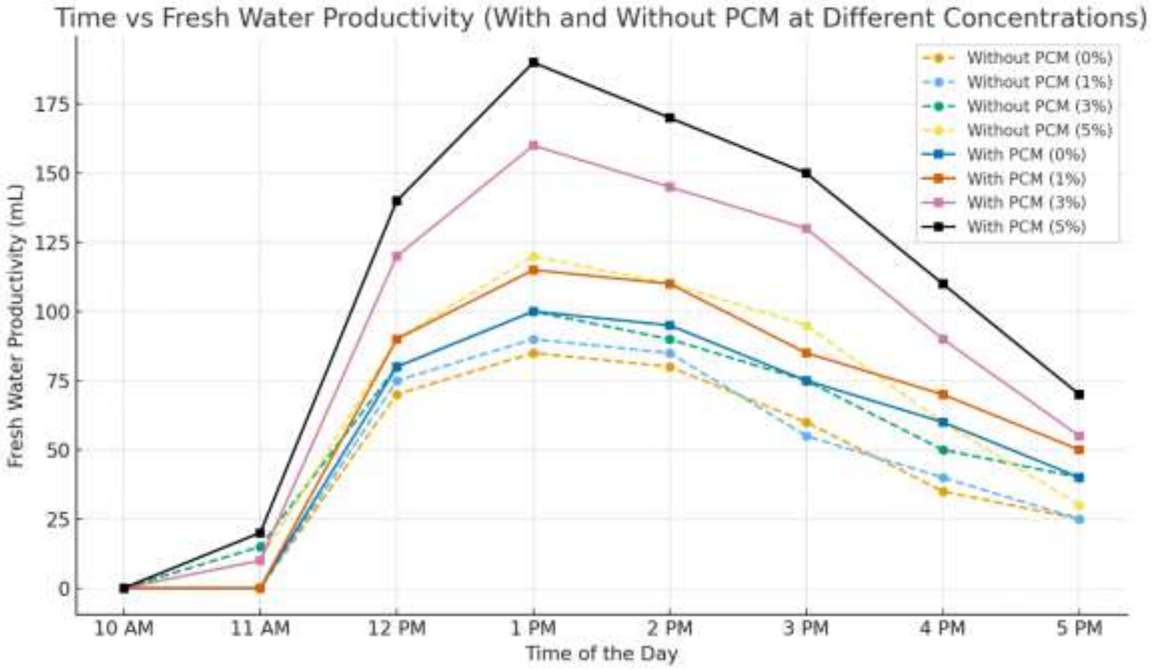

Figure 10: Variation in Fresh Water Productivity with time of the day (hrs) for different PCM concentrations (with and without nanoparticles)

3.6 Economic Analysis

The economic assessment of the solar stills under different configurations—conventional, PCM-integrated, and nano-enhanced PCM systems are analysed using Eqs. 1 to 7. The analysis highlights a clear trade-off between the higher initial investments required for advanced designs and the long-term operational and economic benefits they provide. The fixed cost of the system increases from $79 for the conventional still to $141 with PCM integration and $177 with nano-enhanced PCM, reflecting the additional material and fabrication expenses. Despite this higher initial cost, the annual operating expenses are notably reduced for advanced systems due to improved thermal storage and efficiency. The conventional system shows an annual operating cost of $4.19, while PCM and nano-enhanced PCM systems reduce this to $2.25 and $2.87, respectively. Although the total annual cost increases from $17.27 (conventional) to $21.25 (PCM) and $27.87 (nano-PCM), this is outweighed by the substantial gain in water yield. Specifically, the annual yield rises from 518.67 l/m² in the conventional design to 802.3 l/m² with PCM and 1062.2 l/m² with nano-enhanced PCM.

This improvement in productivity directly lowers the cost of distilled water per litre. The cost per litre decreases from \$0.033 for the conventional still to \$0.026 with PCM and further to \$0.024 with nano-enhanced PCM. These results establish that while nano-enhanced PCM systems demand higher initial investment, they are the most economically viable option in the long term, as they deliver greater productivity and reduced cost per litre of fresh water.

4. Conclusions

(i). The double-slope solar still (DSSS) without PCM showed the lowest productivity (355 ml/day at 0% nanoparticles), highlighting the limitation of conventional systems in sustaining evaporation during late hours.

(ii). Incorporation of PCM improved thermal stability and yield (450 ml/day at 0% nanoparticles), confirming the role of latent heat storage in extending operational hours.

(iii). Nanoparticle-enhanced PCM further boosted system efficiency, with freshwater yields of 520 ml (1%), 700 ml (3%), and 750 ml (5%), demonstrating that thermal conductivity enhancement significantly accelerates charging and discharging cycles.

(iv). Temperature analysis revealed absorber plate peaks of 62-63 °C, while PCM stabilized near 65 °C during phase transition, ensuring smoother thermal regulation compared to non-PCM cases.

(v). Economic assessment showed higher fixed costs (\$79 → \$141 → \$177 for conventional, PCM and nano-PCM systems respectively), but annual yield improvements (518.67 → 802.3 → 1062.2 litre/m²) reduced the cost of distilled water from \$0.033/l (conventional) to \$0.026/l (PCM) and \$0.024/l (nano-PCM).

(vi). Overall, the DSSS with 5% nanoparticle-enhanced PCM delivered the best balance of productivity, cost-effectiveness and sustainability, establishing it as a promising solution for freshwater production in arid and semi-arid regions.

References

[1]. Khalaf, M. O., Özdemir, M. R., & Sultan, H. S. (2025). A Comprehensive Review of Solar Still Technologies and Cost: Innovations in Materials, Design, and Techniques for Enhanced Water Desalination Efficiency. *Water (20734441)*, *17*(10).

[2]. LISBOA, H., Nascimento, V. R. S., Campos da Silva, A. R., Resende, I. T., Bharagava, R. N., Saratale, R., ... & Romanholo Ferreira, L. F. Solar-Powered Desalination: Advancements in Technology and Predictive Modeling for Sustainable Water Production. *Available at SSRN 4781545*.

[3]. Alawee, W. H., Mohammed, S. A., Dhahad, H. A., Essa, F. A., Omara, Z. M., & Abdullah, A. S. (2021). Performance analysis of a double-slope solar still with elevated basin—comprehensive study. *Desalination and Water Treatment*, *223*, 13-25.

[4]. [Thakur, V. K., Gaur, M. K., Dhamneya, A. K., & Sagar, M. K. (2021). Performance analysis of passive solar still with and without nanoparticles. *Materials Today: Proceedings*, *47*, 6309-6316.

[5]. Sivakumar, V., & Sundaram, E. G. (2013). Improvement techniques of solar still efficiency: A review. *Renewable and Sustainable Energy Reviews*, *28*, 246-264.

[6]. Dhivagar, R., Omara, A. A., Kim, S. C., Balasubramanian, D., Kale, U., & Kilikevičius, A. (2025). Sustainable solar still desalination using beeswax and paraffin wax phase change materials: a 5E comparison toward emerging efficient systems. *Thermal Science and Engineering Progress*, 103994..

[7]. [El-Sebaii, A. A. (2005). Thermal performance of a triple-basin solar still. *Desalination*, *174*(1), 23-37.

[8]. Sahota, L., & Tiwari, G. N. (2017). Advanced solar-distillation systems. *Green Energy Technol*, *10*, 978-981.

[9]. Ranjan, K. R., & Kaushik, S. C. (2013). Energy, exergy and thermo-economic analysis of solar distillation systems: A review. *Renewable and Sustainable Energy Reviews*, *27*, 709-723.

[10]. Fattahi Juybari, H., Parmar, H. B., Rezaei, M., Nejati, S., Oh, J., Alsaati, A. A., ... & Warsinger, D. M. (2024). Unifying efficiency metrics for solar evaporation and thermal desalination. *ACS Energy Letters*, *9*(10), 4959-4975.