Research Article

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Investigation of a Pyramid Solar Still with CuO Nanoparticles-Paraffin Wax Blend as Energy Storage Material

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ABSTRACT

An experimental investigation was conducted to enhance the efficiency of pyramid solar still utilizing CuO nanoparticles as an energy storage medium. The primary objective was to improve water productivity and system efficiency by enhancing thermal energy absorption and storage by integrating copper oxide (CuO) nanoparticles into the phase change material (PCM). The experimental setup includes two systems: a conventional pyramid solar still (CPSS) and a modified version incorporating 0.05% by weight of CuO nanoparticles. The performance was measured using key parameters such as water production, temperature variation, and system efficiency. The pyramid solar still incorporating CuO nanoparticles produced an average water yield of 7.0 litres per day, in contrast to conventional still that produces 3.7 litres per day, indicating 89.19% enhancement in water output. The modified still achieved a maximum water temperature of 72 °C, whereas the conventional system reached 61.5 °C. The research indicates that integrating CuO nanoparticles into pyramid solar still distinctly improves water production and thermal efficiency, presenting a viable approach for increasing freshwater generation in arid and semi-arid areas.

Keywords: Pyramid solar still; Thermal efficiency; Productivity; CuO nanoparticles; Distillate.

1. INTRODUCTION

Water shortage presents an extreme global issue. The Earth possesses an abundant quantity of water; however, its uneven distribution leads to a limited availability across various geographical regions. Many methods have been developed to purify salt water in response to the freshwater shortages in developing nations in recent decades. Salt can be separated from seawater *via* desalination methods. Millions of people worldwide still rely mainly on the water generated by traditional desalination procedures, but these processes are costly and need a significant amount of electricity. Each desalination method operates with specific requirements which makes it impossible to install these systems in remote locations. Due to the high expenditure of conventional desalination technologies, various alternate methods are being examined to extract freshwater. The desalination procedure utilizing solar power has proven itself as a viable technique for producing fresh water through solar energy. The processes of evaporation and condensation in solar still generate freshwater, making them cost-effective and eco-friendly desalination methods. Many authors have examined several types of solar stills to obtain distilled water (Yuvaperiyasamy *et al.* 2023). A transient mathematical model shows that the distillate produced by traditional solar still using stearic acid as a phase change material (PCM) under the basin is directly proportional to the mass of the PCM (Kateshia and Lakhera, 2022). A layer of PCM, which releases thermal energy stored during the day as sensible heat, latent heat, or a mix of the two in the evening, may be added to solar distillation systems to increase their efficiency (Kumar *et al.* 2022; Nakade *et al.* 2024). The study examined the impact of adding 10 mm thick PCM to the base of the solar still basin and it was found to boost the output by 20% (Sonker *et al.* 2022). Senthilkumar *et al.* (2024) evaluated the performance of solar stills which incorporated paraffin wax under the weather conditions of Chennai, India. The study shows PCM enhances the thermal conductivity by increasing specific heat capacity and latent heat of fusion which in turn increase solar still unit efficiency. The study reported on thermal energy storage (TES) materials that absorb heat during sunlight hours and release equivalent energy in discharge mode at sunset, exhibit minimal temperature variation in the solar still (Shabgard *et al.* 2022). Paraffin wax was shown in an experimental investigation to improve thermal energy storage by 61% significantly. Although it is possible to change any pair of phases (gas, liquid, or solid), the transition between liquid and solid phases is the most practical option from an economic standpoint (Arulprakasajothi *et al.* 2024). The single-slope passive solar still system falls into an underdeveloped category of solar still devices, producing lower quantities of distilled water compared to modern solar desalination systems prior to the addition of TES material. (Selimefendigil *et al.* 2022).

A recent research has concentrated on TES materials to increase the efficiency of solar still units. Phase change materials have inherent latent heat properties, that allow them to store and release significant amounts of thermal energy as heat (Bacha *et al.* 2024). A single-slope solar (SSS) still using paraffin wax was designed in comparison to a conventional solar still, resulting in a 400% increase in nighttime production (Mehta and Panchal, 2023). Adding highly conductive nanoparticles can accelerate the charging and discharging rates of PCMs (Kumaravel *et al.* 2023; Kumaravel *et al.* 2024). Their passive design dramatically impacts the distillation rate and thermal efficiency of single-slope solar stills. Adding nanoparticles to base PCM is projected to increase the distillation rate of the solar stills (Kumar *et al.* 2021; Mustafa *et al.* 2024). When nanoparticles are added to base materials, a single-slope passive solar still's efficiency and the overall distillate production are increased (Suraparaju and Natarajan, 2021). When Al_2O_3 nanoparticles were added to paraffin wax, the study found that the stability of the homogenous mixture and thermal conductivity were significantly improved (Chaichan and Hussein, 2018). Elashmawy *et al.* (2024) examined the effect of utilizing materials with varying potentials on the productivity of solar stills with a specific focus on the condensing surface. The study evaluated the influence of nano-silicon addition to condensing surfaces on dropwise and film wise condensation in solar stills. The results revealed that the incorporation of nanomaterials modifies the condensation process for each material, facilitating droplet formation rather than film formation.

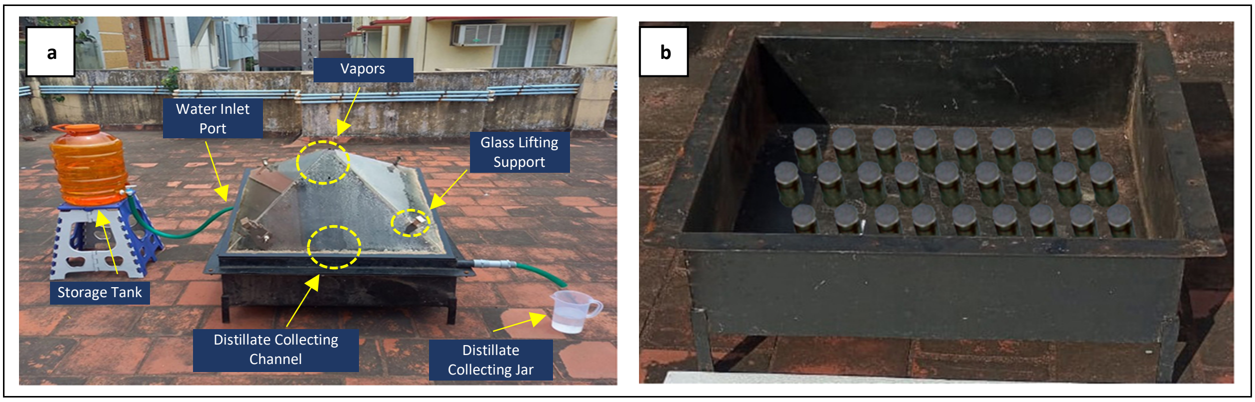

Fig. 1: (a) Depicts the experimental setup (b) Incorporation nCuO and paraffin wax in solar still

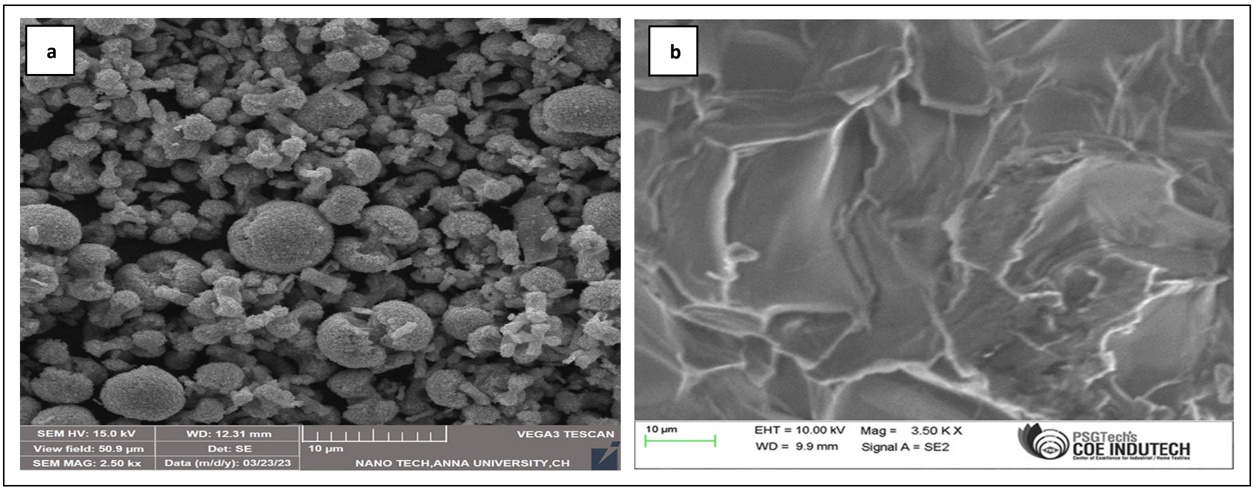

Fig. 2: SEM images of nCuO and paraffin wax

Pyramid solar stills that use phase change materials and nanoparticles to boost output have not been extensively studied in the literature. The efficiency of pyramid solar stills is enhanced in this work by using paraffin wax and CuO nanoparticles as energy storage medium. In addition, it seeks to compare and contrast the output of conventional solar stills with modified solar still.

Table 1. Properties of nCuO and paraffin wax

S. No.	Property	nCuO	Paraffin Wax
1.	Thermal Conductivity	20W/m·K	0.2 W/m·K
2.	Melting Point	1,200 ℃	46 ℃
3.	Heat Capacity	0.65 J/g·K	2.1-2.4 J/g·K
4.	Thermal Stability	Stable up to 1,000 ℃	Decomposes above 300 ℃

2. EXPERIMENTAL SETUP AND PROCEDURE

Fig. 1 shows the experimental setup with the solar still (SS) basin filled with nCuO and paraffin wax. The still's basin, measuring 0.30 m², is made of galvanized iron, while the collector surface is made of acrylic. Acrylic provides a 2% higher light transmission than glass, along with superior impact resistance, and enhanced visual clarity. The material properties used in the experiment are detailed in Table 1. Experiments were conducted from 7:00 am to 7:00 pm. In the pyramidal solar still, a small glass barrier is placed on the collector's inner surface to gather fresh water. A flexible hose connection facilitates the transfer of condensed water to a measuring container. Thermocouples are used to measure the temperatures of the basin, water, glass, and surrounding environment. An anemometer measures wind speed, while a solar power meter scales solar intensity.

3. PREPARATION OF nCuO AND PARAFFIN WAX BLEND

The nCuO and paraffin wax were obtained from ultra-nanotech private limited in Bangalore and were handled with care. The size of the nCuO are 20-50 nm. Paraffin wax was melted at 46°C in a suitable container using a heat source (Bharathiraja *et al.* 2024). A gradual incorporation of 0.5 wt% nCuO into the molten wax was carried out with continuous stirring speed of 500 rpm to ensure uniform dispersion. Continuous stirring was employed to facilitate dispersion and prevent the sedimentation of nanoparticles. The mixture was allowed to cool gradually with intermittent stirring to prevent agglomeration or settling of the nanoparticles during the wax solidification process. The stirring process continued until the mixture reached room temperature (Bharathiraja *et al.* 2023). The properties of the nanoparticle-paraffin wax composite were assessed. The blended nanocomposite was placed within a stainless-steel container at the base of the solar still. Fig. 2(a) and 2(b) present SEM images of nCuO and paraffin wax, respectively.

4. RESULTS AND DISCUSSION

The experiments were conducted on May 28, 2024, from 7:00 am to 7:00 pm in Pongalur, Tamil Nadu, India. The experimental results were recorded at hourly intervals.

4.1 Variaton of Solar Intensity and Wind Velocity

Fig. 3 illustrates the relationship between wind speed and solar intensity on the day of experiment. The data analysis indicates that solar radiation reached a maximum of 1208 W/m^2, while the average wind speed was recorded at 1.50 m/s. Solar radiation intensity directly affects water evaporation in solar desalination systems. Increased intensity improves evaporation and freshwater production, while weather-related fluctuations can affect system efficiency. Wind speed influences heat transfer and cooling processes. Moderate winds enhance heat dissipation; however, high wind speeds may result in significant heat loss. Optimizing the efficiency of a solar desalination system necessitates a precise equilibrium between the utilization of solar intensity and the influence of wind effects (Yuvaperiyasamy *et al.* 2024).

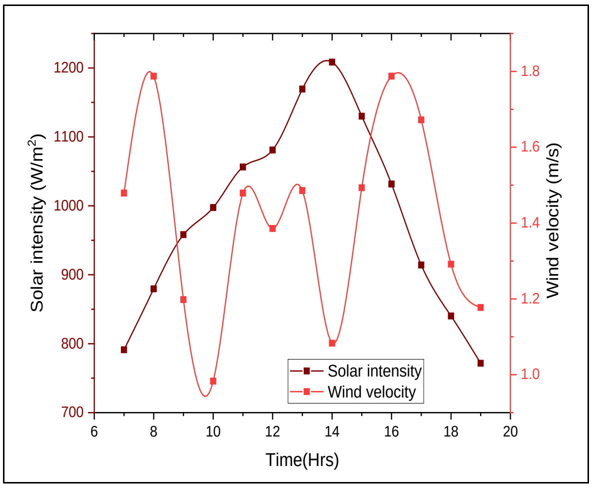

Fig. 3: Variation of solar intensity and wind velocity

4.2 Temperature Profile of Conventional and nCuO Enhanced Solar Still

Fig. 4 compares the temperature profiles of a CPSS and a CuO nanoparticle-enhanced solar still over 12 hours, showing how the integration of nanoparticles affects thermal behavior. Both solar stills exhibit a comparable temperature of approximately 30 ℃.

Throughout the day, the temperature of the CuO nanoparticle-enhanced still rises rapidly than that of the conventional still, achieving a peak temperature of approximately 72 °C by 12 pm, in contrast to around 61.5 °C for the conventional still. This suggests that CuO nanoparticles, recognized for their elevated thermal conductivity, enhanced heat absorption and retention, resulting in an increased water temperature. Following the attainment of their maximum temperatures, both stills exhibit a gradual decrease in temperature. The modified solar still exhibits prolonged temperature retention, indicating superior energy storage capabilities and a reduced rate of cooling. This characteristic is essential for enhancing the productivity of the solar still, as elevated temperatures promote increased evaporation, leading to greater water condensation (Sathyamurthy, 2023).

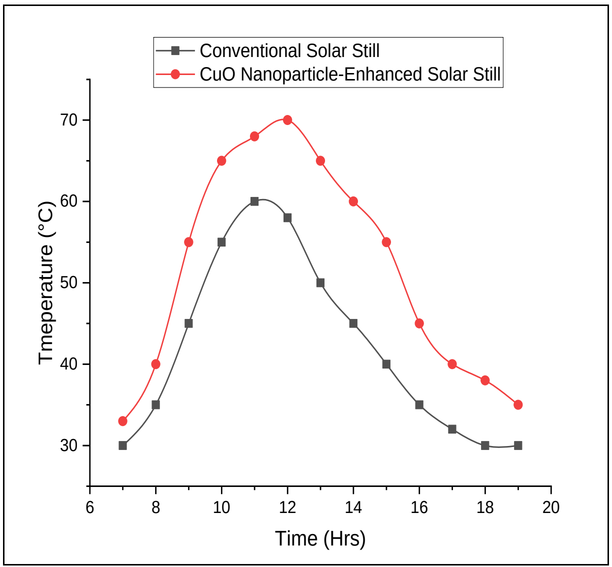

Fig. 4: Temperature profile for conventional and CuO nanoparticle-enhanced solar still

4.3 Hourly Productivity Comparison Between Conventional and nCuO Enhanced Solar Still

Fig. 5 illustrates the hourly productivity of a CPSS and a CuO nanoparticle-enhanced solar still, demonstrating the advantage of the enhanced still. Productivity increases in the morning, reaching a peak around 1:00 PM, followed by a decline as the solar intensity decreases. The CuO-enhanced still achieves a peak productivity of approximately 800 mL, markedly surpassing the conventional still's peak of 350 mL, attributable to enhanced heat absorption and thermal efficiency induced by the nanoparticles. The findings indicate that the inclusion of CuO nanoparticles enhances the overall efficiency of solar still, rendering them a more viable choice for solar desalination and water purification applications (Kibria *et al.* 2024).

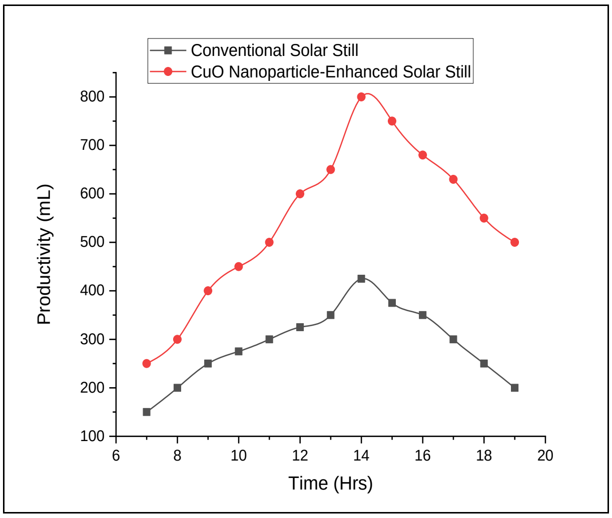

Fig. 5: Hourly productivity of conventional and CuO Nanoparticle-enhanced solar still

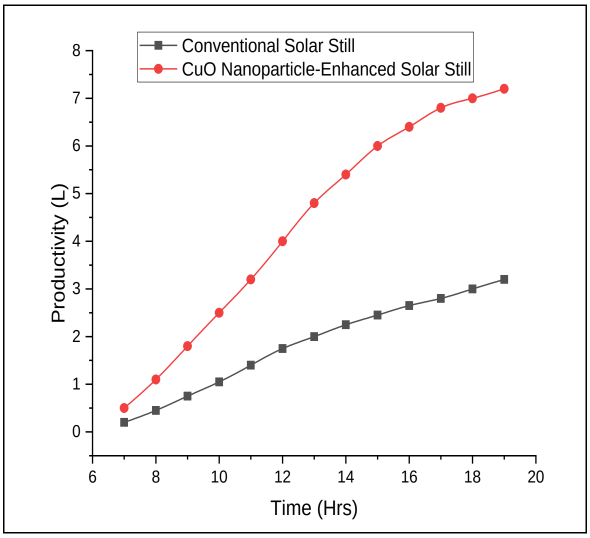

Fig. 6: Cumulative productivity of conventional and CuO nanoparticle-enhanced solar still

4.4 Cumulative Productivity of Conventional and nCuO Enhanced Solar Still

Fig. 6 demonstrates that CuO nanoparticle-enhanced solar still significantly outperforms CPSS regarding cumulative water productivity. At the end of the day, the enhanced still achieved a total productivity of 7.0 L per day, which is more than twice that of the conventional still (3.7 L per day). The improvement is uniform throughout the cycle, with the CuO-enhanced still demonstrating a more pronounced increase in cumulative yield at hourly intervals. The incorporation of CuO nanoparticles improves heat absorption and evaporation rates, leading to a total water yield that is 89.19% higher than that of the conventional design. This illustrates the significant advantage of integrating nanomaterials into solar desalination systems to enhance efficiency. The observed difference demonstrates that CuO nanoparticles substantially enhance the evaporation rate through improved heat absorption and thermal efficiency. The cumulative productivity of the nCuO-enhanced still increases at a steeper rate throughout the day, demonstrating its superior efficiency in converting solar energy into distilled water. The enhanced performance is particularly evident during midday (Zayed *et al.* 2024).

5. CONCLUSION

According to the study, the productivity and thermal efficiency of pyramid solar still are significantly increased when CuO nanoparticles are incorporated into the PCM. The overall water output of the modified solar still with CuO nanoparticles was almost double. The peak water temperature rose to 72 ℃, compared to the 61.5 ℃ recorded in the traditional system, due to the enhanced heat absorption and retention properties of the CuO nanoparticles. The enhanced thermal efficiency led to increased evaporation rates, thereby significantly improving freshwater production. The results indicate that the incorporation of nanomaterials into solar desalination systems provides an effective solution to address water scarcity.

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CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest.

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