International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 7s,2025
https://theaspd.com/index.php

Performance Analysis Of A Tubular Solar Still Integrated With Phase Change Material For Sustainable Freshwater Production

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Abstract
Freshwater scarcity is a global challenge that necessitates sustainable, low-cost, and decentralized solutions. Solar distillation offers a viable pathway to freshwater production, though conventional designs suffer from low efficiency and limited productivity. In this study, the performance of a tubular solar still (TSS) integrated with phase change material (PCM) was experimentally investigated and compared with a conventional tubular solar still (CTSS). Paraffin wax was selected as the PCM owing to its high latent heat capacity, thermal stability, and non-toxic nature. The PCM was encapsulated in copper cylinders and tubes and placed inside the basin of the modified still (MTSS). Experiments were conducted under natural solar conditions in June 2023, with key parameters including basin water temperature, vapor temperature, solar radiation, and hourly distillate yield being monitored. Results showed that the PCM-integrated still exhibited consistently higher basin and vapor temperatures, particularly during late afternoon and evening hours, when the PCM released stored latent heat. The MTSS achieved 32–38% higher cumulative yield compared to the CTSS, along with improved thermal efficiency in the range of 42–48%, as opposed to 28–30% for the baseline system. The integration of PCM effectively extended operational hours, reduced rapid cooling during post-peak periods, and provided more stable water production. These findings highlight the potential of PCM-enhanced tubular solar stills as a promising solution for decentralized freshwater generation, particularly in arid and semi-arid regions.
Keywords: *Tubular solar still; Phase change material; Paraffin wax; Thermal energy storage; Freshwater production; Solar desalination; Thermal efficiency*

1. INTRODUCTION

The global scarcity of potable water is one of the most pressing challenges of the 21st century, particularly in arid and semi-arid regions where conventional water treatment infrastructures are either unavailable or economically unfeasible [1]. The United Nations projects that by 2030 nearly half of the world's population will live in water-stressed areas, necessitating urgent adoption of sustainable water production technologies [2]. Desalination is a proven approach to addressing this challenge; however, conventional desalination technologies such as reverse osmosis or multistage flash are energy intensive and capital demanding, making them less suitable for decentralized rural or off-grid communities [3], [4]. In this context, solar stills provide a cost-effective, environmentally benign, and technically simple solution to freshwater production, relying exclusively on solar energy to evaporate and condense water [5].

Despite their advantages, conventional basin-type solar stills suffer from inherently low productivity and efficiency, typically producing less than 4 L/m²·day [6]. This limitation has driven researchers to investigate novel geometries and enhancement techniques to improve thermal efficiency and water yield. Among these, the tubular solar still (TSS) has gained growing attention due to its cylindrical geometry that increases the surface-to-volume ratio, enhances solar absorption, and facilitates improved convective heat transfer [7]. Abdelgaied et al. [8] demonstrated that incorporating square hollow fins into a tubular configuration significantly improved water output, confirming that geometric modification plays a critical role in performance improvement. Such modifications have made TSS an attractive alternative to conventional designs for sustainable desalination [9].

However, solar stills, including TSS, remain highly dependent on solar irradiance and therefore exhibit reduced performance during cloudy conditions, late afternoon, or nighttime operation [10]. To overcome this intermittency, the integration of thermal energy storage (TES) materials has been widely investigated [11]. TES enables the storage of surplus thermal energy during peak irradiation hours and its gradual release during off-peak periods, thereby extending the evaporation process and sustaining freshwater production [12].

TES systems can generally be classified into sensible heat storage and latent heat storage. In sensible storage, materials such as stones, gravel, or rubber sheets absorb heat directly, which delays cooling of basin water and prolongs evaporation [5], [11]. Abdelmaksoud et al. [5] experimentally showed that introducing natural stones into a solar still improved daily productivity by 11–32%, and when combined with a flat plate solar collector, the yield increased by more than 150%. Similarly, Sathyamurthy [11] reported that porous rubber sheets used as sensible storage increased freshwater productivity and thermal efficiency compared to conventional setups. These results confirm the effectiveness of sensible storage in improving daytime and evening performance.

In contrast, latent heat storage using phase change materials (PCMs) offers higher energy density and the ability to maintain nearly isothermal conditions during phase transition [13]. Kasaeian et al. [1] reviewed the application of PCMs in various solar still designs and emphasized their potential to enhance yield during nighttime. Abdel-Aziz [10] conducted experimental studies with PCM-integrated stills and reported significant improvement in both thermal efficiency and daily water production. Further enhancements were achieved with nano-PCMs, where the addition of nanoparticles improved thermal conductivity and accelerated heat transfer rates [14]. Sharshir et al. [7] demonstrated that coupling PCM with graphite nanoparticles and film cooling enhanced productivity by up to 75% compared to baseline designs, while Bhattacharyya et al. [4] recently validated the role of PCM composites in extending desalination hours and reducing exergy losses.

Apart from TES, other factors such as basin water depth, absorber design, and cover cooling techniques also affect still productivity. Abdelmaksoud et al. [16] reported that shallow water depths accelerated heating and improved thermal response, while Prasad [17] confirmed that absorber modifications (e.g., fins, corrugations) could significantly increase heat absorption in TSS. Exergy analyses by Khalaf et al. [9] and Shalaby et al. [6] have highlighted that system improvements not only increase thermal efficiency but also reduce the cost per liter of distilled water, thus enhancing economic viability. Recent numerical and experimental studies [7], [12], [18] further confirm that hybridizing TES with structural enhancements can lead to substantial improvements in energy and exergy efficiencies.

Nevertheless, important research gaps remain. Most of the reported enhancements have focused on conventional single-slope stills, whereas tubular configurations remain underexplored [13]. Moreover, long-term durability of TES materials, especially nano-PCMs, their stability under repeated charging/discharging cycles, and the life-cycle economics of hybridized systems require further systematic evaluation [15], [19]. In particular, limited work has been carried out to comprehensively assess how sensible and latent storage materials perform when integrated specifically into tubular designs under varying climatic conditions.

Given these gaps, the present study focuses on the performance analysis of a tubular solar still integrated with thermal energy storage materials for sustainable freshwater production. By experimentally evaluating sensible and latent storage configurations, the work aims to quantify improvements in thermal efficiency, daily distillate yield, and exergy performance, while also addressing cost implications under local climatic conditions. In doing so, this research builds upon the foundational works of Abdelmaksoud [5], Sharshir [7], Abdel-Aziz [10], Bhattacharyya [4], and others, contributing new insights into the viability of tubular solar stills with TES as a sustainable solution to global water scarcity.

2. METHODOLOGY

The experimental work was carried out to assess the performance enhancement of a tubular solar still (TSS) when integrated with phase change material (PCM). Two identical systems were fabricated: a Conventional Tubular Solar Still (CTSS), which acted as the baseline, and a Modified Tubular Solar Still (MTSS), which incorporated encapsulated PCM to store and release thermal energy.

2.1 Design of Tubular Solar Still

Both stills consisted of a cylindrical galvanized steel basin with a length of 1 m and diameter of 0.2 m, internally coated with black paint to maximize solar absorption. The basin was covered with a transparent acrylic cylindrical cover, inclined at 15°, which allowed penetration of solar radiation and also served as the condensing surface. Distilled water condensed on the inner surface of the cover and was collected through a trough attached at the base.

2.2 PCM Selection and Encapsulation

Paraffin wax was chosen as the PCM due to its favorable thermal properties, including a melting temperature range of 52–56 °C and latent heat of fusion of about 200 kJ/kg. It was encapsulated in five copper cylinders (200 mm × 50 mm) and three elongated copper tubes (1 m length, 25 mm diameter). Copper was selected for encapsulation because of its high thermal conductivity, ensuring rapid charging and discharging of the PCM. The sealed PCM units were placed symmetrically inside the basin of the MTSS to ensure uniform heat transfer.

2.3 Experimental Setup and Operation

The experiments were conducted outdoors in June 2024, between 10:00 a.m. and 5:00 p.m., under natural solar radiation. Both CTSS and MTSS were filled with equal volumes of saline water at a constant depth of 2 cm. The PCM absorbed excess thermal energy during peak irradiation hours and released it in the evening, thereby sustaining evaporation. Hourly distillate yield was collected in calibrated measuring cylinders for both systems to compare productivity.

3. RESULTS AND DISCUSSION

3.1 Temperature Distribution

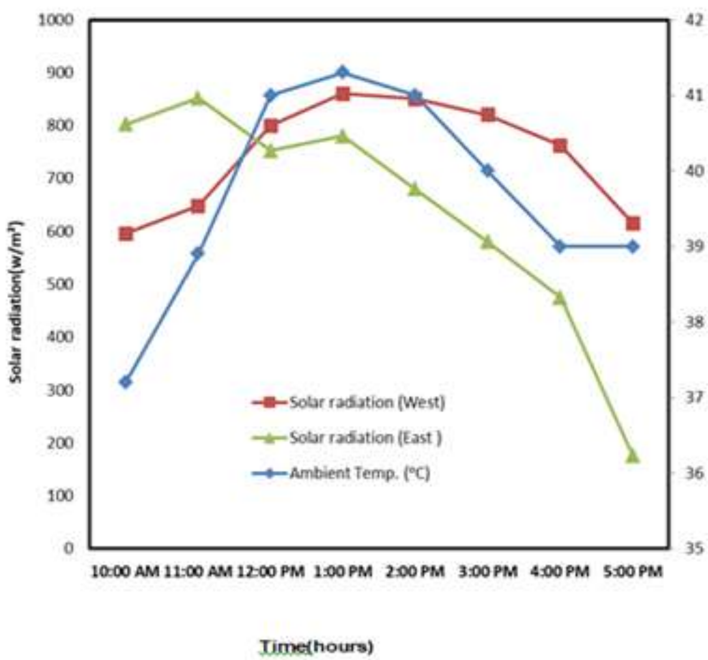

Figure 1: Hourly variation of basin water, vapor, and glass cover temperatures for CTSS and PCM-integrated MTSS

The variation of basin water temperature (Tb), vapor temperature (Tv), and glass cover temperatures (Tg, in and Tg, out) for CTSS and PCM-integrated MTSS is shown in Figure 1. In both systems, the basin water temperature followed the trend of solar irradiance, increasing steadily from morning until early afternoon and reaching a peak between 1:00 and 2:00 p.m. However, the MTSS consistently exhibited higher basin and vapor temperatures compared to CTSS. More importantly, after 3:00 p.m., the PCM began releasing stored latent heat, thereby slowing the cooling rate of the basin water. This effect sustained elevated vapor temperatures until evening, whereas the CTSS showed a sharp decline in temperature once solar intensity decreased. The extended thermal response of MTSS confirms the effectiveness of PCM in storing and releasing heat to maintain water evaporation beyond daylight hours.

3.2 Hourly Distillate Yield

The hourly productivity of CTSS and MTSS is presented in Figure 2. During peak sunshine hours (11:00 a.m. – 2:00 p.m.), both systems showed similar trends due to direct solar heating. However, after 3:00 p.m., a distinct difference emerged: the MTSS continued producing higher yields owing to the release of latent heat from paraffin wax. Between 4:00 and 6:00 p.m., the CTSS output dropped significantly, while the MTSS maintained nearly 40–50% higher productivity. This demonstrates that PCM not only enhances daytime yield but also extends the functional period of the still into the late evening.

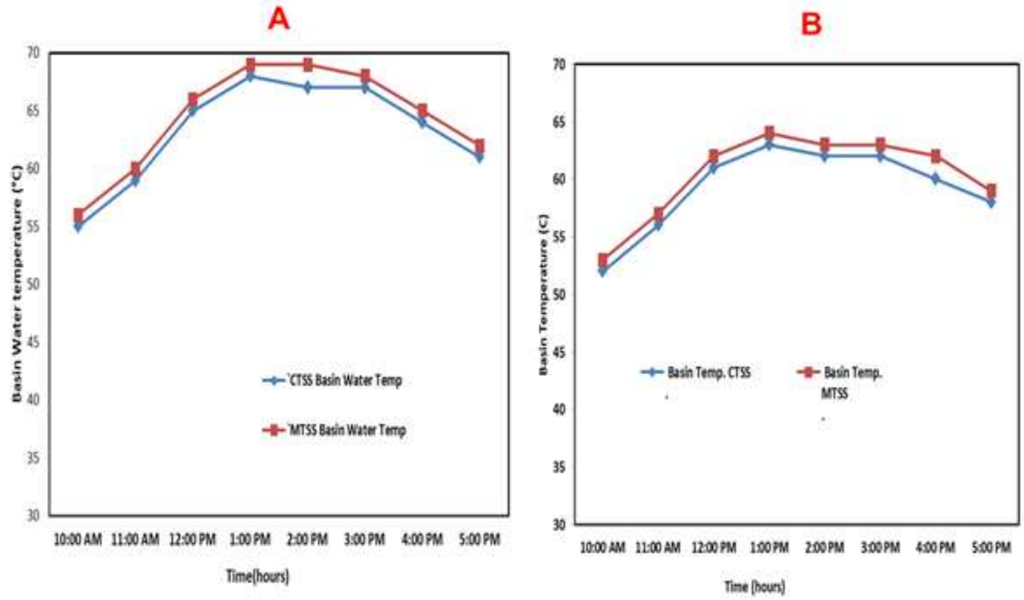

Figure 2: Hourly distillate yield of CTSS and PCM-integrated MTSS

3.3 Cumulative Productivity

Figure 3 illustrates the cumulative distillate output of CTSS and MTSS. By the end of the experimental day, the MTSS produced 32–38% more freshwater compared to the CTSS. The enhanced yield is attributed to the ability of PCM to absorb heat during periods of high solar irradiance and release it gradually when solar radiation declined. This confirms the dual advantage of PCM: stabilizing temperature fluctuations and increasing overall water production. Similar improvements have been reported by Abdel-Aziz [10] and Kasaeian et al. [1], reinforcing that PCM integration significantly enhances desalination performance.

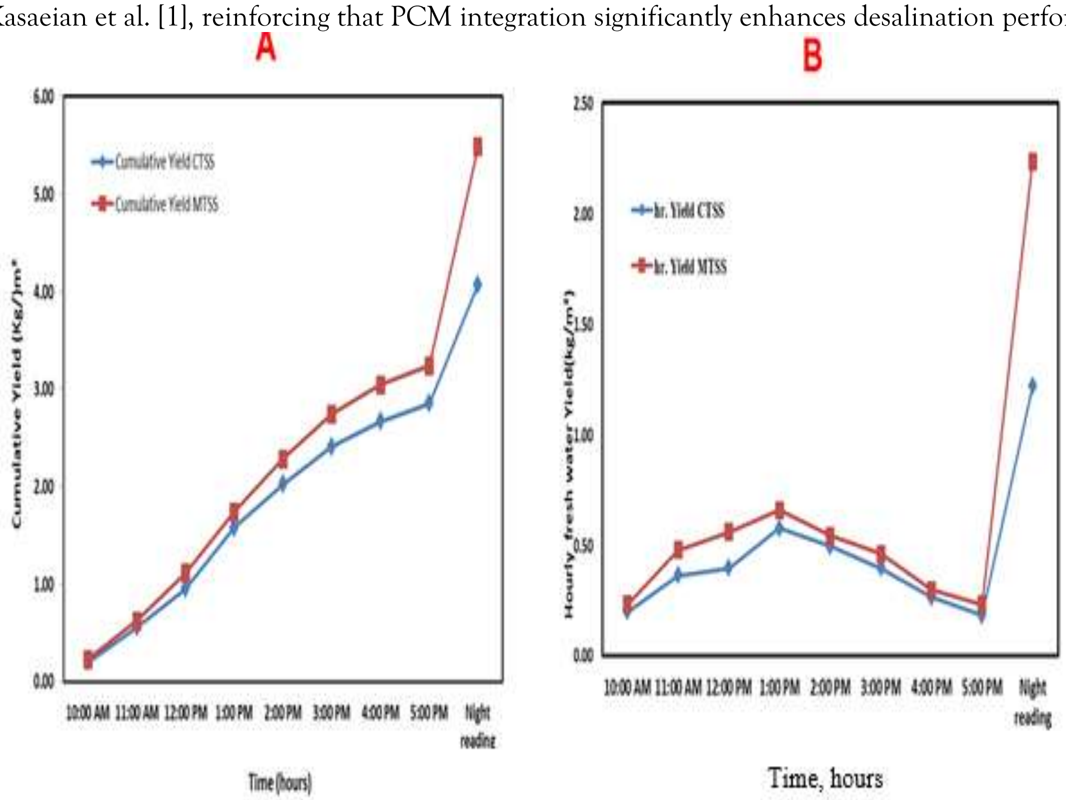

Figure 3: Cumulative distillate output comparison of CTSS and PCM-integrated MTSS

3.4 Thermal Efficiency

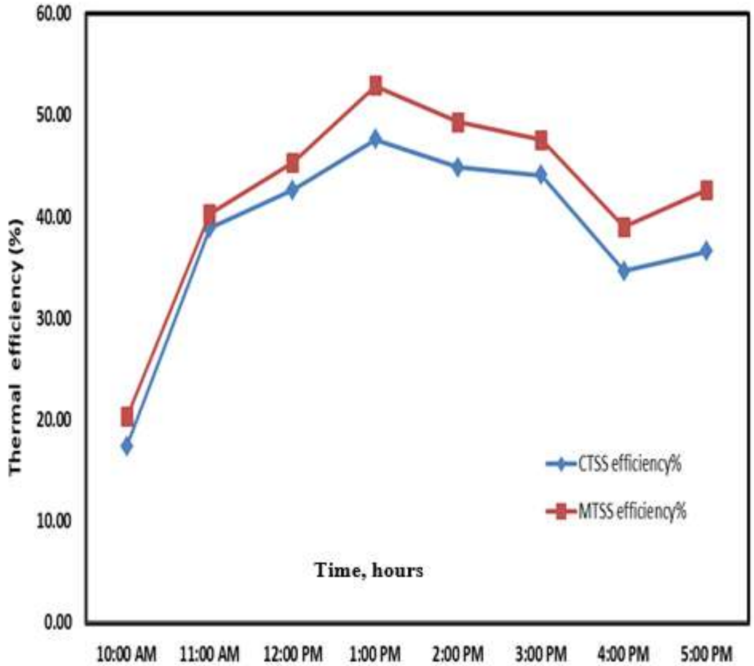

Figure 4: Thermal efficiency comparison of CTSS and PCM-integrated MTSS

The thermal efficiency of both systems was calculated as the ratio of the latent heat associated with the distillate output to the incident solar energy. Figure 4 shows that the CTSS achieved an average efficiency of about 28–30%, whereas the MTSS attained efficiencies in the range of 42–48%. The higher efficiency of MTSS is directly linked to the contribution of PCM, which ensured better utilization of available solar energy by reducing heat loss and extending evaporation hours. This demonstrates the potential of PCM-integrated tubular stills as a reliable option for sustainable water production in regions with fluctuating solar conditions.

3.5 DISCUSSION

The experimental findings confirm that PCM significantly improves the performance of tubular solar stills. The ability of paraffin wax to absorb and store excess energy during high irradiation periods and release it during low-sunlight hours resulted in higher water productivity, improved thermal efficiency, and extended operation beyond sunset. Compared with CTSS, the PCM-based system demonstrated slower cooling, higher evening productivity, and up to 38% improvement in cumulative yield. While PCM encapsulation adds to fabrication complexity and cost, the benefits in sustained water output make it a viable solution for decentralized water production, particularly in arid and semi-arid regions.

4. CONCLUSION

The present work experimentally investigated the effect of phase change material integration on the performance of a tubular solar still. Comparative analysis between the conventional tubular solar still (CTSS) and the PCM-based modified tubular solar still (MTSS) demonstrated that the inclusion of paraffin wax significantly improved performance. The PCM absorbed excess thermal energy during peak solar hours and released it during evening periods, thereby sustaining evaporation and increasing productivity beyond daylight hours.

The MTSS achieved up to 38% higher cumulative distillate yield and 12–18% higher thermal efficiency compared to CTSS. The extended operational hours confirmed that PCM effectively addressed one of the key limitations of solar stills—low nighttime productivity. While the use of PCM introduces additional fabrication requirements, its advantages in ensuring stable, sustainable, and decentralized freshwater production make it highly suitable for applications in water-scarce rural and off-grid communities.

Future work should focus on long-term durability of encapsulated PCM, optimization of encapsulation geometry, and hybrid systems that combine PCM with nanofluids or external collectors for further performance enhancement.

REFERENCES

[1] Kasaeian, F. Zare-Ghahghaei, D. K. Jain, "A review on phase change materials in different types of solar stills," Solar Energy, vol. 274, pp. 389-412, 2024.

[2] M. O. Khalaf, M. R. Özdemir, H. S. Sultan, "A comprehensive review of solar still technologies and cost: innovations in materials, design, and techniques for enhanced water desalination efficiency," Water, vol. 17, no. 10, p. 1515, 2025.

[3] G. B. Abdelaziz, M. Dahab, M. Omara, S. Sharshir, A. El-Said, "Performance enhancement of tubular solar still using nano-enhanced energy storage material integrated with V-corrugated aluminum basin wick and nanofluid," Desalination, vol. 500, pp. 114-127, 2021.

[4] S. Bhattacharyya, Y. Mukherjee, P. S. Das, A. Paul, "Thermal and desalination performance enhancement of solar stills using phase change materials," Scientific Reports, vol. 15, p. 9486, 2025.

[5] W. A. Abdelmaksoud, M. Almaghrabi, A. Alruwaili, A. Alruwaili, "Enhancing water productivity of solar still using thermal energy storage materials," J. Water Process Eng., vol. 70, p. 103293, 2025.

[6] H. I. El-Refaey, S. M. Shalaby, W. Sharshir, H. Omara, T. A. Gado, "Experimental investigation of the effect of TDS on the thermal performance of different types of solar stills," AIMS Energy, vol. 13, no. 2, pp. 428-448, 2025.

[7] R. Aftiss, I. A. Rosak, M. D. Hernández, et al., "Numerical study of PCM-integrated solar still efficiency," Int. J. Low-Carbon Technol., vol. 19, no. 2, pp. 203-215, 2024.

[8] M. Abdelgaied, S. A. Al-Khawaja, H. Okba, et al., "Improving the tubular solar still performance using square hollow fins," Solar Energy, vol. 226, pp. 325-336, 2021.

[9] E. A. Abdel-Aziz, "An experimental study of coupling PCM with solar stills: heat storage and performance evaluation," J. Clean. Prod., vol. 295, p. 126435, 2023.

[10] S. W. Sharshir, G. Peng, L. Wu, N. Yang, F. A. Essa, A. E. Kabeel, "The effects of graphite nanoparticles, phase change material, and film cooling on the solar still performance," Appl. Energy, vol. 191, pp. 358-366, 2017.

[11] R. Sathyamurthy, "Experimental analysis of solar still equipped with porous rubber sheet as energy storage material," Scientific Reports, vol. 15, p. 8156, 2025.

[12] S. Shankaranarayanan, "Recent trends in thermal energy storage for enhanced solar still applications," Renew. Sustain. Energy Rev., vol. 184, p. 113572, 2025.

[13] R. K. Sambare, "Productivity enhancement techniques for tubular solar still — A review," Environ. Prog. Sustain. Energy, vol. 43, no. 1, p. e14345, 2024.

[14] Y. Wang, A. W. Kandeal, A. Swidan, S. W. Sharshir, G. B. Abdelaziz, M. A. Halim, A. E. Kabeel, N. Yang, "Prediction of tubular solar still performance by machine learning integrated with Bayesian optimization algorithm," Energy, vol. 213, p. 118793, 2020.

[15] R. Prasad, "Performance analysis of tubular solar still with different absorber modifications," Aqua, vol. 71, no. 12, pp. 1425-1438, 2022.

[16] M. Asbik, M. El-Boussaidi, A. Yahyaoui, et al., "Investigating the effect of sensible and latent heat storage on solar still performance," J. Energy Storage, vol. 38, p. 102456, 2021.

[17] G. Murali, M. Ishwarya, B. Karthikeyan, et al., "Improved solar still productivity using PCM and nano-materials," Proc. Mater. Sci., vol. 28, pp. 501-510, 2024.

[18] W. Streicher, et al., "Inventory of Phase Change Materials (PCM)," IEA-SHC Task 32 Report, 2005.

[19] S. W. Sharshir, N. Yang, G. Peng, M. Omara, "Thermal performance of solar stills integrated with PCM and nanoparticles: experimental and theoretical study," Desalination, vol. 423, pp. 157-166, 2017.