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REVIEW ARTICLE

Technical review on active and passive solar stills to improve the performance of enhanced condensers using nanoparticles

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ABSTRACT

As the global population continues to grow, the need for freshwater is becoming increasingly urgent. It has increased the acceptance of desalination technology, with solar stills emerging as popular, low-cost, and low-maintenance options. However, solar energy still suffers from low freshwater production, and hence, there is a need to evaluate different approaches utilised by researchers to increase productivity. This study presents a systematic review of various active and passive solar stills and the modifications incorporated in their designs to increase productivity. Furthermore, this study also explores the significant advancements in the context of nanoparticles and condensers used to improve the performance of solar stills. To ensure a huge spread in the adoption of solar still-applied science, ongoing research is necessary. The findings of the research work offer findings and data on the continuing state of Solar still applications and suggest possible areas for future research. Finally, this study can aid in the creation of economical and sustainable solutions to expanding freshwater needs.

Keywords: solar desalination; phase change material; solar still; nano particle; productivity

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1. Introduction

The escalating need for pure water in contemporary society has been spurred by the rise of diverse industries and factories, leading to the pollution of natural resources [1]. Conversely, numerous regions across the globe with arid conditions are characterised by scant rainfall and restricted groundwater access. Unfortunately, the majority of water sources, such as rivers and lakes, exhibit elevated saline and brackish levels, rendering them unsuitable for consumption, agricultural use, and household needs [2]. Thus, solar Desalination has emerged as a reliable, environmentally conscious, and economically viable approach for producing drinkable water to meet the needs of people living in rural regions. By harnessing solar energy, this method can effectively eliminate impurities, such as salt and other materials from brackish water, making it safe and feasible for different types of applications. This specific method bears the possibility of offering a continuous supply of edible and drinking water to areas that do not have infrastructure or tackle other limitations [3].

Scientists are diligently engaged in the advancement of desalination facilities to secure a sufficient future water supply for human needs. Various desalination techniques have been employed to obtain fresh water from sources contaminated by salinity and adulteration.

As part of these approaches, solar stills provide an accessible, easy and cost-effective technology for producing potable water [4]

There are two primary types of solar stills: one active Solar still and a second passive solar still. Several factors hinge on the product of solar stills, including ambient temperature, solar intensity, wind speed, condition disparity between water and glass, absorber plate dimensions, water exposed surface area, glass inclination, inlet water temperature, and water depth[5].

Many inventive designs exist today, spreading across the right from pyramidal to hemispherical and even from single-slope to double solar stills[6]. Moreover, there are specific solar still models that have seen a huge augmentation with supplementary elements such as wicks, fins, modified absorber plates, and energy storage components, hence increasing the efficiency levels. Certain sun stills use solar radiation to evaporate both freshwater and saltwater, taking advantage of the greenhouse effect, even though their yield is still lower than that of other water deionisation techniques such as reverse osmosis and multi-effect desalination[7].

Various academics have time and again engaged in the investigation, as well as the examination of multiple active and passive solar still configurations [8]. According to the research they conducted, double-slope solar stills have shown higher performance than single-slope ones, and both fall in the category of passive solar stills.[9] Further research on the changes within solar still basin liners has provided us with a wide range of innovative remedies. These include the addition of phase-change materials to dynamic adjustments [10]. These modifications have a huge influence on productivity and have been subjected to a full analysis. Furthermore, the impact of definite basin liner varieties on productivity was investigated, including examinations of various layouts and water levels. Fins, wicks, nanofluids, nanostructures, and dynamic adjustments are examples of contemporary internal improvements that have highlighted the creative spirit of researchers in this field.[11-14]

The current review article presents diverse solar distillation systems, both with and without the incorporation of Phase Change Materials, with the aim of identifying modifications that enhance their overall efficiency. The structure of the article is organised as follows: Section 1 offers an introduction and an extensive overview of the historical progression of various solar stills. The principles of solar stills are discussed in Section 2, followed by a detailed analysis of related literature in Section 3.

2. Fundamentals of solar still

A solar still (SS) is a tightly sealed container designed to convert saline water to drinkable water. A shallow basin is installed in the structure that holds brackish water, which is then exposed to solar radiation, causing the water temperature to rise tremendously and eventually evaporate. The inside of the vessel is usually covered with a dark hue that boosts the sun's energy within it. The upper cover of the Solar still is also crafted in a manner that emits immense solar radiation transmittance. Therefore, that kind of material is used, such as glass or plastic. This expedites the water vapour condensation and droplet movement. The insulation of solar stills, which are made up of four walls and a shallow basin, is an important component that must be carefully installed to reduce energy loss[14].

3. Literature reviews on passive solar stills:

Abdullah et al.[15] assessed solar still (SS) devices constructed and examined at diverse convex altitudes, utilising different wick materials, in addition to applying Nano (Ag) black and dark paint and Nano PCM within the context of the Kingdom of Saudi Arabia (KSA). They successfully established a condensing area with a tilt angle matching the testing location's altitude (24°), and they held the view that further refinements have the potential to elevate the overall efficiency.

The influence of the CuO/GO nanocomposite on a disposed stepped Solar still has been examined, yielding noteworthy results from Ajdari and Ameri [16]. The introduction of 0.03 weight percent CuO and GO resulted in freshwater output increments of 48.12% and 81.59%, respectively. At a capacity percentage of 30/70 for CuO/GO, the utilisation of the nanocomposite led to an 81.59% increase in the freshwater volume. Although possibilities for enhanced efficiency persist, researchers are encouraged to explore higher concentration ratios.

A pioneering redesign involving a convex dish absorber was shown as a standby substitute for the traditional flat absorber liner by Saleh et al.[17]. This dish-style solar distiller incorporates a circular base and a cotton wick as an additional wetting component. This study investigated the influence of various water depths on the authorisation of a dish dome, with measurements of 1, 3, 5, 7, 9, and 12 cm. Remarkably, the dish solar distiller exhibited the highest thermal efficiency when utilising a (PCM) at a water depth of 9 cm, resulting in a remarkable 62.4% efficiency, in contrast to the traditional distiller's 30%.

In this study, Abdullah et al.[18] implemented a straightforward and cost-effective modification to increase the yield of tubular solar stills (TSS). This study evaluated the efficiency of Inclined Tubular Solar Stills (ITSS) with three distinct inclination angles (2°, 4°, and 6°) in comparison to TSS operating without inclination. Notably, the ITSS-PCM-Ag configuration demonstrated a thermal performance of 43.5% and a daily output that surpassed that of the TSS by 62.5%. Although this setup may not be optimal for local applications, its performance remains remarkable.

Kumar et al.[19] conducted a study to verify the achievement of a traditional one-sloped solar still using available crude wax. To accomplish this, three solar stills were constructed. The findings demonstrate that still incorporating non-doped phase change material (NDPCM) yielded an impressive 65.17% more drinkable water than the standard still. Subsequently, the CW Still produced 50.24% more water. This study suggests that under varying conditions, it is possible to increase the mass percentage of ZnO nanoparticles for further enhancement.

Selimefendigil et al.[20] presented an experiment to examine the impact of incorporating copper oxide (CuO) nanoparticles on the single-slope Solar still performance. The utilisation of these nanoparticles led to notable improvements in both the energy and exergy efficiency levels, increasing from 15.96% to 19.90% and from 1.25% to 2.01%, respectively.

Goshayeshi et al.[21] conducted an investigation that presented experimental findings of an innovative approach involving the integration of graphene oxide nanoparticles and paraffin. This research explored the combination of paraffin with paraffin and graphene oxide within absorbers of semicircular, triangular, and rectangular shapes, each with mass percentages of 0.1, 0.3, and 0.5. The outcomes revealed that semicircular absorbers demonstrated the most favourable performance, yielding an output of 1.55 $kgm^2\ h^{-1}$ after 15 hours. Triangular absorbers produced 1.48 $kgm^2\ h^{-1}$, and rectangular absorbers yielded 1.3 $kgm^2\ h^{-1}$. These absorber designs have the potential to investigate the behaviour of nanomaterials such as Fe3O4 in a magnetic field with constant or varying field strength.

Rufus et al. [22] designed and fabricated double solar stills comprising a traditional design along with a customised version, both possessing an area of 1 m^2. These stills were constructed using aluminium plates and featured a 4 mm clear glass cover, inclined at 12º to align with the altitudes of Vellore, Tamil Nadu, India. Given the elevated risks associated with the use of Carbon Nanotubes (CNT), it is imperative to conduct comprehensive research aimed at identifying and developing sustainable energy storage materials.

In a recent research endeavour, the preservation of heat as a resource and the enhancement of the district heating system's efficiency was achieved using nanoparticle and phase change material (PCM) for treating desalination water by Shoeibi et al. [23]. The incorporation of an anthracite porous surface bed facilitated the augmentation of the solar radiation. Notably, the application of the PCM and the introduction of the permeable surface absorber yielded increments of 39.03%, 26.55%, and 17.09%, respectively. It is important to acknowledge that these additional enhancements contribute to a notable increase in overall cost.

Essa et al. [24] conducted a study that aimed to improve the efficiency of a tubular solar still with a spinning drum (TDSS) by employing nanoparticle coatings, a phase-change material, and a solar dynamic concentrator. The research also investigated the effectiveness of the TDSS with regard to different drum rotation speeds. The thermal capability of the conventional Solar still (CSS) stretches from 32% to 34%. Notably, the TDSS incorporating PCM attained the highest thermal efficiency at 0.3 rpm, reaching an impressive 63.8%.

A passive solar still consolidated with a thermal storehouse apparatus was meticulously calculated to distil the brackish water by Asbik et al.[25]. The central element of the conjectural arrangement was an insulated rectangular basin coupled with a distillation system linked to a heat storage system housing three distinct materials: paraffin wax, sand, and air. Notably, the daily efficiency of sand and phase-change material (PCM) storage media exhibited significant enhancements, surpassing regular solar stills by 152.80% and 223.09%, respectively. Further investigations should be conducted to optimise the operational parameters of solar stills across different seasons.

Shoeibi et al.[26] selected nano-enhanced phase-transition materials, porous media, and nano-enhanced absorption techniques to increase the efficiency of solar Desalination. Saltwater was introduced to enhance the solar energy absorption capability of anthracite media. Notably, the daily energy efficiencies of CSSA-NA-NP1, CSSA-NA-NP3, CS SA-NA-NP2, and CSSA-NA-NP4 exhibited significant improvements of 42.7, 37.5, 55.8, and 49.5%, respectively, compared to the standard Solar still.

Abdelaziz et al. [27] devised five distinct combinations for increasing the effectiveness of tubular solar stills. The most advanced configuration involves a V-shaped basin with a wick, incorporating 1.5 wt% CB nano-fluid and 3 wt% CB nanoparticles within paraffin wax beneath the basin. This optimal arrangement resulted in a remarkable increase of 82.16% in thermal energy efficiency and an impressive increase of 221.8% in exergy efficiency.

Suraparaju et al. [28] improved the production of drinkable water in single-slope solar stills by utilising a hollow-finned absorber basin immersed in paraffin wax. The study encompassed separate experiments investigating the effect of hollow-finned absorber basins on solar still output, with and without considering the Phase Change Material (PCM). The utilisation of hollow-finned absorber basins led to a 15.7% increase in energy efficiency for SSHF (single-slope solar stills with hollow-finned absorbers (SSHF) and a remarkable 52.4% increase for SSHFP (single-slope solar stills with hollow-finned absorbers and PCM). However, large-scale water production remains challenging.

In a study by Abdelgaid[29], supplementary catalysts were applied to augment the competence of the tubular Solar still. Copper hollow fins were strategically affixed to the soaked surface. When juxtaposed with the standard configuration, the daily efficiency of the tubular solar system was significantly improved by the inclusion of hollow square and hollow circular fins, with gains of 33.1% and 47.4%, respectively. Kateshia and Lakhera[30] devised a methodology that incorporates a Phase Change Material (PCM) and pin fins as absorptive components within a single slope solar still. They conducted a comprehensive exploration encompassing three distinct scenarios: a standard solar still (Case I), a solar still integrating phase change material (Case II), and a solar still combining pin fins with phase change material (Case III). The analysis revealed that solar stills equipped with PCM (Case II) attained an impressive maximum efficiency of 52%, whereas solar stills enhanced with both PCM and pin fins (Case III) achieved an even more remarkable efficiency of 57%.

Jahanpanah et al. [31] conducted an exploratory investigation into the impact of a low-temperature phase-change material (PCM) on an enhanced single-slope solar still. The study involved three distinct test conditions: a solar still lacking a PCM, a solar still integrated with 3 kg of PCM, and a solar still featuring 6 kg of PCM.

The utilisation of 6 kilograms of PCM yielded a notable 30.3% enhancement in the output and an 8.29% increase in efficiency. To obtain the best result, more research should be conducted to dive deeper into the varying PCM quantities. [30]

Sonker et al. [32] mixed nanoparticles (CuO) with PCM (paraffin wax) and stored the mixture to increase heat conductivity, and the mixture was placed in a copper cylinder. This increased the total daily output of the solar distillery unit. The daily yields of the Solar Still with Phase Change Material (SSPCM) and Solar Still with Nano-Enhanced Phase Change Material (SSNPCM) showed impressive improvements of 40.5% and 94.19%, respectively, when compared to a traditional Single Slope Solar still (SSS). The performance of the Solar still can be further improved by investigating various shapes of copper cylinders.

A comprehensive analysis was conducted by Kabeel et al. to gauge the effectiveness of a single-slope, single-basin solar still design intended for solar systems.[33]. Using numerical models and experimental tests, solutions were explored for various challenges, including glass and water cover temperatures, novel materials, and the implementation of nanoparticle vehicle liners. Notably, Solar, still equipped with a Freshwater wall (FWCW), exhibited an impressive productivity exceeding 9.429 kg m^{-2} per day.

Rufus et al.[34] comprehensively inspected and assessed a solar still integrated with a nanoparticle-enhanced phase change material (NPCM). Different types of materials, including CuO, TiO2, and GO, have also been introduced. In contrast to the fecundity of the traditional stills, substantial improvements were observed: 23.0% for SSPCM, 39.3% for SSNPCM-1, 43.2% for SSNPCM-2, and 18.0% for SSNPCM-3. Further investigation of the enhancement of the CuO nanoparticle fraction is required.

Shanmugan et al[35]. investigated the incorporation of (Al2O3) nanoparticles within wick materials for a solar still employing a Phase Change Material (PCM) for Thermal Energy Storage (TES). Solar energy still demonstrated efficiencies of 59.14% during summer and 27.13% during winter. Additionally, the utilisation of black paint should be further explored to investigate additional nanoparticle enhancements.[38]

Mohammed et al.[36] established optimal values for several key parameters, including solar radiation, water mass, phase change material (PCM) mass, and nanoparticle-enhanced PCM (NPCM) mass. Commonly utilised paraffin wax (PCM) and Al2O3 nanoparticles have been studied to enhance their specific thermal properties. Their research primarily focused on major active attributes. It was observed that higher salinity of water in the basin led to reduced daily water productivity.

Moreno et al.[37] A transient numerical analysis was conducted to inspect the effects of energy storage using eBody phase change material (PCM) on the base of a solar still. This research was directed at understanding the blow of various PCM materials with different phase transition temperatures and latent heat. Four different materials were tested in this study. The RT70 HC test for this scenario included three PCM thicknesses: 1, 0.5, and 0.25 cm. The output of the study displayed a comprehensive enhancement in performance, with an increase from 55.78% to 66.70%. This study provides valuable opportunities for exploring the possibilities of phase change material (PCM) in energy storage applications.

Kannan et al.[38] assessed Heat Storage Systems (HSS) combined with PCMs in triangular and square configurations and compared 3-can and 4-can setups with HSS without PCM. In these configurations, PCM plating of aluminium cans resulted in a 92.8% (square) and 67.12% (triangular) improvement in freshwater production. To maximise the heat transfer for better evaporation and output, they advise investigating several PCM-filled container layouts (square, triangle, and linear). The potential of PCMs to improve water production in HSS is highlighted in this study.

Grewal and Kumar[39] used paraffin wax in a stepped solar still (SSS) to produce clean water and concentrated sugarcane juice. They evaluated three SSS modules (S1, S2, and S3) in copper tubes with different amounts of PCM (450 g, 900 g, and 1350 g). Unit U3 exhibited a 43.33% higher energy efficiency than U1 and U2, surpassing them by 25.04% and 7.31%, respectively. This study highlights the potential of PCM integration into SSS for enhanced product concentration, clean water generation, and energy efficiency.

Agrawal and Singh [40] assessed the efficiency and hourly production of conventional and modified double-slope single-basin solar stills incorporating eutectic Phase Change Material (PCM) through an experimental study. They employed a multiphase, three-dimensional Computational Fluid Dynamics (CFD) model using ANSYS FLUENT 19.2 workstation. A difference of 9.06% was observed between the experimental and simulation results. The daily energy efficiency for the experiment was 30.42%, whereas the simulated value reached 33.15%. This simulation methodology is promising for improving the energy coherence of solar stills in similar exploratory contexts.

Kumar and Jegadheeswaran[41] investigated a conventional Solar Still (CSS) with four components: basin, glass cover, insulation material, and condensate collection channel. They enhanced this by extending the square fins beneath the basin lining by 25 mm. The glass was inclined at a 12-degree angle toward the south and aligned with the latitudes of the testing site in Coimbatore, India. However, productivity in both CSS and Single Slope Water Float (SSWF) is constrained when sunlight is absent. This study suggests prospects for boosting CSS productivity through design and structural modification.

Sampathkumar and Natarajan[42] proposed an innovative method to amplify the competence of single-slope solar stills. By strategically utilising naturally generated agar-agar fibres in the absorber basin and incorporating optimal weight percentages of micro-phase-change materials beneath it, an experimental study showed a remarkable 26.24% enhancement in Solar still productivity. Introducing agar-agar fibres in varying quantities—5g, 10 g, 20 g, 30 g, and 40 g) resulted in productivity improvements of 16.21%, 23.14%, 21.53%, and 5.15%, respectively. This paper presents an operative method for augmenting Solar still performance.

Ho et al.[43] enhanced the regulation of traditional passive solar stills for purification by implementing solar irradiation concentration based on refraction. They utilised two passive double-slope single-basin solar stills integrated with Fresnel lenses (FRL) and phase-change materials. The FRL-linked prototype achieved the highest water output of 3.19 L/m2 /d. The FRL design increased productivity to 37%, which is a significant improvement over the 28% of the traditional design. The system performance can be further optimised by incorporating properly configured PCM storage.

Sampathkumar and Natarajan[44] aimed to boost single-slope solar still output by subsuming micro-PCM heat storage beneath the basin and increasing palm flower powder in the basin. Their experiments tested different amounts of palm powder (10–150 g). The highest productivity (37.25%) was achieved with 50 g of palm powder. Other quantities (10, 30, 70, 100, 120, 150 g) led to productivity increases of 11.85%, 24.78%, 36.8%, 33.05%, 10.25%, and 20.22%. Future research could explore the thermal properties of mixed micro- and nanoparticles and other phase-change materials.

Hansen et al.[45] enhanced the daily distillation output by combining inclined and traditional solar stills. External additions such as flat, sloped, and fin-shaped absorbers were integrated. Connecting the inclined still with the fin-shaped absorber to a basin resulted in an enhanced production of 74.5%. Productivity rose by 87.96% when it was attached to the PCM and basin.

Abed and Hachim[46] developed an altered tubular solar still (TSS) by applying black paint to the basin. They employed various types of heat storage: two phase-change materials (PCMs), paraffin wax, and stearic acid. Considering the PCM mass, wind speed, solar radiation, and ambient temperature, they found that TSS with 40 mm PCM (2.664 kg paraffin wax, 3.143 kg stearic acid) performed better throughout the day compared to TSS without PCM.

Al-Hamadani and Yaseen[47] devised an innovative multistage solar distillation system equipped with a photovoltaic heater. This setup employed a DC water heater and solar radiation to heat the saltwater, resulting in a notable 33% increase in freshwater production. Nevertheless, the efficiency of freshwater production notably decreases as the glass cover is heated.

Mohammed et al.[48] investigated the efficiency of single-slope Solar still by incorporating RT42PCM with weights of 2 kg, 4 kg, and 6 kg. Their findings indicated daily average efficiencies of 68, 57.2, and 53.6%, respectively. They recommended implementing enhancements, such as automated cleaning and flushing of the Solar still, to improve its performance further.

Vigneswaran et al.[49] utilised a low thermal conductivity material to enhance the Solar still yield in conjunction with a PCM. They constructed a galvanised iron basin as a reference in their study. The capitulate of ABSS was 4.36 L/m2/day, surpassing that of GIBSS and CSS by 10.1% and 19.1%, respectively. Additional configurations involving PCM were also explored.

Khalilmoghadam et al.[50] enhanced solar stills by integrating dormant heat storage with a built-in capacitor. Tests were conducted to assess efficiency. The results showed a significant improvement from 23.7% to 48.5% compared with the original design. Further cost reduction is possible if PCM and PHP prices decrease in the future.

Khanmohammadi and Khanmohammadi[51] conducted comprehensive research to analyse the performance of a cascade solar still desalting system incorporating diverse insulation and seclusion types and phase-change materials. Their study employed tri-objective optimisation for two distinct scenarios of Solar still desalination units, with total annual cost (TAC), energy competence, and exergy-based CO2 diminution as the key goal functions. The energy performance assessment revealed that Case I, utilising nePCM II in conjunction with phenolic foam insulation, achieved an efficiency of 7.68%. In contrast, Case II, employing paraffin and glass wool, yielded an efficiency of 7.54%.

Sonker et al. [52] investigated a stainless steel single-slope solar still with a thickness of 1 mm, enhanced by incorporating a copper container filled with a phase change material (PCM). The PCM-loaded copper containers were tactically set up inside the solar still basin as part of the study, and the effects of variations in water depth between one and five centimetres were examined. [65]

Yousef and Hassan[53] examined two strategies for improving the energy and exergy performances of solar desalination units. First, they introduced a heat sink with pin fins (PF) into a phase change material (PCM) to enhance its thermal conductivity. Second, the PCM was integrated with black steel mesh fibres (SWF) in the Solar still basin. Four different Solar still configurations were compared with traditional stills, resulting in notable improvements in daily energy efficiency: 5.9% without PCM, 13.2% with PCM, 17.3% with PCM-PF, and 21.6% with PCM-SWF. The energy efficiency figures consistently outperformed those of the evaluated scenarios.

Sarhaddi et al.[54] investigated the energy and exergy generation of two cascade solar stills, one with weirs and another without, both incorporating PCM storage. The absorber plate accounted for the highest dissipation rate, constituting 83.1% and 78.8% of the system for solar stills without PCM on average clear days and solar stills with PCM on semi-cloudy days, respectively.

Ansari et al.[55] developed transient mathematical models to study the Desalination of brackish water. They achieved this through passive Solar still integrated with a heat-energy storage device beneath the basin liner. Solar radiation reaching the water through the condensing glass cover facilitates the heating process. The study emphasised the need for economic analysis when implementing such a system. **Table 1** shows the analysis in tabular form to express researchers' work on passive solar stills with modifications to enhance distillate output.

Table 1. Analysis of the Passive Solar still modifications to enhance distillate output.

Researcher	Modification/Material Used	Key Findings
Abdullah et al. [15]	Nano (Ag) black, dark paint, Nano PCM, wick materials	Improved efficiency of SS devices; further refinements are recommended.
Ajdari & Ameri [16]	CuO/GO nanocomposite	Increased freshwater output by 48.12% (CuO) and 81.59% (GO).
Saleh et al. [17]	Convex dish absorber, PCM	Achieved 62.4% efficiency at 9 cm water depth, compared to 30% for traditional distillers.
Abdullah et al. [18]	Inclined Tubular Solar Stills (ITSS), PCM, Ag coating	43.5% thermal efficiency, 62.5% increase in daily output.
Manoj Kumar et al. [19]	Crude wax, NDPCM	NDPCM increased water yield by 65.17% and CW Still by 50.24%.
Selimefendigil et al. [20]	CuO nanoparticles	Energy efficiency increased from 15.96% to 19.90%; exergy efficiency from 1.25% to 2.01%.
Goshayeshi et al. [21]	Graphene oxide nanoparticles, paraffin	Semicircular absorbers gave the best output (1.55 kgm^2 h^{-1}).
Dsilva Winfred Rufuss et al. [22]	Double solar stills, aluminium plates	Highlights CNT safety concerns; calls for sustainable materials.
Shoeibi et al. [23]	PCM, porous anthracite bed	Efficiency increased by 39.03%, 26.55%, and 17.09% with modifications.
Essa et al. [24]	Tubular Solar Still with spinning drum, PCM, nanoparticle coatings	TDSS-PCM achieved 63.8% efficiency at 0.3 rpm.
Shoeibi et al. [26]	Nanoparticles, PCM, porous media	Maximum daily efficiency increase of 55.8%.
Abdelaziz et al. [27]	V-shaped basin, CB nano-fluid, CB nanoparticles in paraffin wax	82.16% thermal efficiency, 221.8% increase in exergy efficiency.
Suraparaju SK et al. [28]	Hollow-finned absorber basin, PCM	Energy efficiency increased by 52.4% (SSHF with PCM).
Abdelgaid et al. [29]	Copper hollow fins	Increased efficiency by 33.1% (square fins) and 47.4% (circular fins).
Kateshia & Lakhera [30]	PCM, pin fins	52% efficiency with PCM; 57% with PCM + pin fins.
Jahanpanah et al. [31]	Low-temperature PCM	30.3% output increase, 8.29% efficiency improvement.
Sonker et al. [32]	CuO-PCM (paraffin wax)	SSNPCM showed a 94.19% daily yield improvement.
Dsilva Winfred Rufuss et al. [34]	CuO, TiO2, GO-enhanced PCM	Performance improvement: SSNPCM-2 (43.2%), SSNPCM-1 (39.3%).
Shanmugan et al. [35]	Al2O3 nanoparticles in wick material	59.14% efficiency in summer and 27.13% in winter.
Muntadher Mohammed et al. [36]	PCM (paraffin wax), Al2O3 nanoparticles	High salinity reduced daily water productivity.
Moreno et al. [37]	PCM energy storage	Performance enhancement from 55.78% to 66.70%.
Thamarai Kannan et al. [38]	PCM in triangular/square configurations	92.8% (square) and 67.12% (triangular) improvement.
Grewal & Kumar [39]	PCM in stepped SS	Energy efficiency increased by 43.33%.
Agrawal & Singh [40]	PCM in double slope SS, CFD modelling	Experiment efficiency: 30.42%; Simulation: 33.15%.
Sathish Kumar & Jegadheeswaran [41]	Square fins beneath the SS basin	A lack of sunlight still constrains CSS.
Sampathkumar & Natarajan [42]	Agar-agar fibers, micro PCM	26.24% enhancement in Solar still productivity.

Researcher	Modification/Material Used	Key Findings
Ho et al. [43]	Fresnel lenses, PCM	Increased productivity from 28% to 37%.
Sampathkumar & Natarajan [44]	Micro PCM, palm flower powder	Best productivity (37.25%) with 50g palm powder.
Samuel Hansen et al. [45]	Inclined still with fin absorber, PCM	87.96% productivity increase.
Abed & Hachim [46]	Tubular SS with PCM (paraffin wax, stearic acid)	Best performance with 40 mm PCM.
Al-Hamadani & Yaseen [47]	Multistage SS with PV heater	33% increase in freshwater production.
Mohammed et al. [48]	RT42PCM	Daily average efficiencies: 68% (2 kg), 57.2% (4 kg), 53.6% (6 kg).
Vigneswaran et al. [49]	Low thermal conductivity materials, PCM	Yield improvement of 19.1%.

Table 1. (*Continued*)

Emphasising improvements in Solar still technology, the table notes materials and changes that increase efficiency and water output, which are shown in **Table 1**. Much research has looked at how phase change materials (PCM), improved absorber designs, and nanoparticles might be included to maximise Solar still performance. Freshwater production, thermal efficiency, and exergy efficiency have been much raised by using CuO, Ag, TiO_2, and graphene oxide nanoparticles. Material advances have proven great efficacy as certain designs using nano-enhanced PCM and composite materials show efficiency increases of over 80%.

By raising sun absorption and heat retention, the combination of parabolic concentrators, Fresnel lenses, and tubular solar stills has helped to increase performance further. Significant efficiency gains have come from changed absorber configurations, including stepped designs, hollow-finned, V-shaped basins, and pin fins. Enhanced heat performance and water generation have also been shown by tests with convex dish absorbers, inclined stills, and spinning drum systems.

Thermal energy storage has benefited much from PCM-based adaptations, which let solar stills remain efficient late at night. Comparisons of several PCM forms and geometric configurations show that some forms—such as square layouts and stepped designs—have the best efficiency increases. While research employing micro PCM and organic additives has optimised distillation rates, multi-stage systems using hybrid PV heaters have further enhanced freshwater output.

Solar still efficiency and productivity have generally improved significantly as absorber design, nanoparticle integration, and PCM-based energy storage have developed. These developments, taken together, have made solar distillation a more practical and effective means of producing freshwater sustainably, with great possibility for improvement by structural changes and material choice.

4. Literature reviews on active solar stills:

Abdullah et al. [56] conducted a comprehensive analysis of three distinct solar-still configurations. These included conventional Solar still (CSS) and two thermosyphon solar stills (TSS), all integrated with CuO nanoparticles. The glass cover of each Solar still functioned as a condensing surface set at a tilt angle of 240 °. Notably, the forced circulation thermosyphon Solar still (FTSS) exhibited a remarkable 196% surge in daily water output compared with the conventional Solar still. Moreover, theoretical investigations hold the potential to optimise the tray diameters and finned absorber dimensions, further enhancing the overall performance.

Alqsair et al. [57] conducted a study to improve the efficiency of a drum solar still (DSS) by utilising a phase-change material (PSC). The design parameters included an opening width of 150 cm and a rim angle of 400 °. Through the incorporation of nanocomposite (NC), PSC, and external condenser in the DSS setup, researchers achieved a significant enhancement. The peak increase in the output reached approximately 320%, resulting in an impressive effectiveness level of 72%.

In Tehran, Parsa et al. [58] introduced a comprehensive system incorporating photovoltaic modules, thermal modules, two solar stills (SSs), a phase-change material, and a turbulator. The photovoltaic modules were positioned facing south at an inclination of 35 °relative to the horizon. There is potential for further investigation in the realm of thermoelectric-based systems by analysing experiments with varying solar still geometries to determine the most efficient configuration. [78]

Abdelgaied et al. [59] investigated a stepped solar distiller featuring three impactful hybrid enhancements: incorporation of phase change materials (PCMs) beneath the steps, integration of interior mirrors, and application of CuO nanoparticles to the absorber surfaces. Through these modifications, the enhanced stepped solar distiller achieved a significant enhancement in the estimated daily energy efficiency with a remarkable 187.4% increase, resulting in a value of 7.96%.

Felemban et al. [60] conducted a study to assess the effects of utilising three distinct absorber liners: a convex plate absorber, a stepped absorber, and a corrugated absorber. These configurations were compared with those of a conventional solar distiller. The corrugated absorber configuration, which also incorporated wicks and an energy storage material, exhibited a significantly improved performance. It achieved a remarkable 69.5% increase in thermal efficiency and approximately 183% higher production than the standard solar distiller configuration.

Younes et al. [61] investigated four types of solar stills: flat wick (FWSS), corrugated wick (CWSS), half-barrel wick (BWSS), and conventional wick (CSS). Evaporation area improvements in the CWSS and BWSS enhanced efficiency. CSS and CWSS, with PCM, had efficiencies of 35% and 54.5% and costs of $0.028 and $0.023 per litre, respectively, showing the impact of design enhancements.

Tafavogh and Zahedi [62] developed a hybrid renewable energy system (HRES) comprising ground-based heat pumps, microalgal culture ponds, parabolic troughs, solar stills, photovoltaic panels, wind turbines, and proton-exchange membranes for biodiesel production. The HRES achieved 67.1% efficiency, and the nanocapsules enhanced CO production and reduced NOx emissions.

Dawood [63] used a phase change material (PCM) to store heat inside an evacuated inner tube. The parabolic trough collector (PTC) possessed a length of 3 m, a rim tilt, and 0.9 an aperture width. In addition, an assessment of the daily production and system efficiency was conducted for the traditional solar system, maintaining oil as the fluid at different flow rates.

Mahmoud et al. [64] devised a solar still combined with a two-effect humidifying distillation unit (SS-HDH). They investigated the influence of the solar concentration ratio and partial solar heat-energy storage on its performance. The highest water yield without PCM reached 11.6 L/m2 per day, featuring an h value of 0.2 m and a CR of 2. Nevertheless, operational and maintenance expenses were notable because of the extensive setup.

Tuly et al. [65] evaluated a solar still SS with a double-slope design and included other components, such as rectangular fins, external condensers, black cotton wicks, and paraffin wax. This study assessed the performance of three double-slope SS across five different scenarios (modified, finned, and conventional). The highest water yields were recorded for the modified, finned, and standard SS, reaching 3.07, 2.70, and 2.46 L/m2, respectively. Although fin and wick materials provide cost-effective heat transfer, the use of PCM and EC manufacturing entails higher expenses.

Dawood et al. [66] examined a study that suggested that Solar still with a stepped slope performs more efficiently when combined with an external solar dish. The experiment included four water flow rates: 250, 350, 450, and 550 mL/min. The incorporation of PCM and sand resulted in augmented daily production rates of 51% and 31% at water spray mass flow rates of 250 mL/min and 550 mL/min, respectively.

Ganesan et al. [67] presented an intriguing research initiative that focused on improving the efficiency of PV/T solar stills. They incorporated a DC-powered blower into a single-slope solar still to enhance the vapour turbulence. Furthermore, a nickel-chromium (NiCr) heater was introduced to expedite the production of purified water. The proposed PV/T solar system showed notable enhancements in both thermal and electrical performance, achieving approximately a 12.5% improvement in the overall thermal efficiency and an 11.5% increase in the electrical performance. This innovative approach demonstrates remarkable performance gains. [94]

Benhammou and Sahli [68] conducted an extensive investigation into single-slope Solar still featuring an innovative energy storage system that incorporated a double-glass solar collector with latent heat storage capabilities. Their model enabled the calculation of the proportion of melted PCM in each sampling period. The novel configuration yielded a significant surge in productivity, showing an impressive increase of 44% in diurnal productivity, 635% in nocturnal productivity, and 63% in daily productivity compared to conventional stills. Maintaining a constant tilt angle throughout the year is crucial for optimising solar applications.

Ghadamgahi et al. [69] extensively examined a five-stage solar still powered by paraffin wax. They explored the water production levels with and without phase change materials (PCMs) at flow rates of 0.7, 1.3, and 1.8 L/min. Their results indicated that a substantial portion (70%) of the total water output originated from the water generation in the first step.

M Abu Arabi [70] examined three different setups: a solar still + glass cooling (SC), a solar still + external collector (SCC), and a solar still utilising a phase-change material (PCM). They incorporated sodium thiosulfate pentahydrate, paraffin wax, and sodium acetate trihydrate as the PCM. By varying the mass flow rate of the coolant from 0 to 10 kg/s, the productivity of the SC, SCC, and SCCP units increased from 1 to 2.14 ml/min, 1 to 6.65 ml/min, and 1 to 7.5 ml/min, respectively. However, the study identified that the overall cost of the PCM materials was relatively high.

Amarloo and Shafii [71] conducted a study investigating the feasibility of incorporating radiative cooling into a solar still. The approach involves integrating a collector that absorbs solar radiation and emits infrared radiation to achieve radiative cooling. By harnessing nocturnal radiative freezing to maintain a cool temperature in the PCM condenser, the daily yield and efficiency improved to 2.805 kg/m2 and 30.7%, respectively. However, owing to the inherent limitations of the cooling capacity of radiative cooling, the inclusion of an air condenser alongside the PCM condenser is required for optimal performance.

Elbar and Hassan [72] developed a single-acting solar still integrated with a photovoltaic module, achieving a notable 11.7% increase in daily productivity through the incorporation of a phase change material (PCM) unit. Additionally, their daily yields saw a significant boost of 19.4% with the inclusion of a floating absorber cover (FAC) that combined CSS, PV, and PCM elements. Further investigation can be carried out to explore the potential of utilising salt water for cooling photovoltaic modules, offering promising avenues for future research in this domain.

Mazraeh et al. [73] introduced an innovative solar still system that integrates phase change materials (PCMs), evacuated tube collectors, and semitransparent photovoltaics. According to their research, the system's highest diurnal energy and exergy yields were 17.93% and 6.95%, respectively, in ideal circumstances involving the use of 10 tubes with PCM at a water depth of 0.03 m. Though the PCM addition improved the efficiency of energy, its impact on exergy efficiency was still quite small.

Al-harassed et al. [74] developed a solar still attached to a solar collector coated with phase change material (PCM). Evaluating the effects of factors such as basin water level, hot water circulation rate, and freezing flow rate on freshwater production were the primary objectives of their study. According to these findings, the system may produce 4300 ml/m2 every day, with approximately 40% of that amount occurring after sunset.

Faegh and Shafii [75] investigated the feasibility of employing phase transition materials for latent heat storage in solar stills. Their system design comprised two evacuated-tube collectors, a brackish water basin, a phase-change material tank, a fan, and 20 thermosiphon heat pipes. This setup led to an 86% increase in yield, resulting in a daily output of 6.555 kg/m2 with 50% greater effectiveness when compared to the system that did not incorporate the PCM.

Kabeel and Abdelgaied [76] conducted an empirical study to assess the efficacy of a cylindrical parabolic concentrator integrated with a focal pipe connected to a solar still featuring an oil heat exchanger and phase change material (PCM). The traditional solar panel still exhibited an efficiency of 46%, whereas the enhanced solar panel consistently achieved a daily efficiency of approximately 25.73%. However, the setup costs for advanced solar panels are notable.

Arunkumar et al. [77] introduced a novel solar still design incorporating a parabolic concentrator (PC) and a storage tank for continuous water circulation. The study featured four distinct operational modes: PC-solar without top-cover cooling, PC-solar + top-cover cooling, PC-solar + PCM, and PC-solar + PCM cooling. Different water flow rates were considered across the scenarios. Additionally, the study demonstrated the prospect of enhancing water heating for higher water absorption in solar parabolic trough collectors by utilising nanofluids. **Table 2** shows the research on active solar stills to enhance distillate output.

Table 2. Research work on Solar still to enhance distillate output.

Author(s)	**Ref. No.**	**Work Done**
Abdullah et al.	[56]	Three solar stills (CSS, TSS) were analysed with CuO nanoparticles; FTSS showed a 196% increase in daily water output.
Alqsair et al.	[57]	Improved drum solar still (DSS) using PSC and NC, achieving a 320% output increase and 72% efficiency.
Parsa et al.	[58]	Developed a hybrid system with PV, thermal modules, solar stills, PCM, and a turbulator in Tehran.
Abdelgaied et al.	[59]	Enhanced stepped solar distiller with PCMs, mirrors, and CuO, achieving a 187.4% efficiency increase.
Felemban et al.	[60]	Compared to absorber liners (convex, stepped, corrugated), the corrugated absorbers improved thermal efficiency by 69.5% and production by 183%.
Younes et al.	[61]	Investigated four SS designs (FWSS, CWSS, BWSS, CSS); CWSS with PCM had 54.5% efficiency, costing \$0.023/L.
Tafavogh & Zahedi	[62]	Developed a hybrid renewable energy system for biodiesel production, achieving 67.1% efficiency.
Khairat Dawood	[63]	Used PCM to store heat in an evacuated tube; assessed daily production and efficiency at varying flow rates.
Mahmoud et al.	[64]	Designed SS with a two-effect humidifying distillation unit; peak water yield reached 11.6 L/m² per day.
Tuly et al.	[65]	Evaluated double slope SS with fins, external condenser, and wick; highest yield: 3.07 L/m² for modified SS.
Khairat Dawood et al.	[66]	Studied stepped SS with an external solar dish; PCM and sand increased production by 51% and 31%.
Ganesan et al.	[67]	Improved PV/T SS using a DC blower and NiCr heater, achieving a 12.5% boost in thermal efficiency.
Benhammou & Sahli	[68]	Investigated double-glass Solar still with PCM, improving diurnal, nocturnal, and daily productivity by 44%, 635%, and 63%.

Author(s)	Ref. No.	Work Done
Ghadamgahi et al.	[69]	Examined five-stage SS with paraffin wax, finding 70% of water output from the first stage.
Abu Arabi	[70]	Compared SC, SCC, and SCCP systems with different PCMs, achieving up to 7.5 ml/min productivity.
Amarloo & Shafii	[71]	Investigated radiative cooling in SS, improving yield to 2.805 kg/m² and efficiency to 30.7%.
Elbar & Hassan	[72]	Developed SS with PV module and PCM, increasing daily productivity by 11.7% and 19.4% with a floating absorber.
Mazraeh et al.	[73]	Integrated PCM, evacuated tubes, and semi-transparent PV, achieving 17.93% energy yield.
Al-harahsheh et al.	[74]	Developed SS with a solar collector and PCM, producing 4300 ml/m² per day, 40% after sunset.
Faegh & Shafii	[75]	Used phase transition materials with thermosiphon heat pipes, increasing yield by 86% to 6.555 kg/m².
Kabeel & Abdelgaied	[76]	A parabolic concentrator SS with an oil heat exchanger was examined, achieving 46% efficiency.
Arunkumar et al.	[77]	Designed SS with parabolic concentrator and PCM, exploring nanofluids for improved heating.

Table 2. (*Continued*)

Table 2 shows current developments in solar still technology, stressing the advantages of nanoparticles, phase change materials (PCM), solar collectors, and hybrid systems in terms of efficiency and water yield. A 320% increase in output has been achieved by including CuO nanoparticles, parabolic solar concentrators, and nano coatings, therefore greatly improving water production. Through the combination of PCM, reflectors, and nanoparticles, stepped solar distillers have also shown really significant efficiency increases.

Performance has been enhanced significantly by absorber changes. Comparative analyses of absorber designs show that corrugated absorbers greatly increase productivity and efficiency. Research on several solar still designs has shown PCM cavity-wick solar stills to be quite efficient with quite low water production costs.

Effective approaches to boost water output have turned out to be hybrid and multi-effect solar stills. Performance has been raised by PV-integrated hybrid systems incorporating PCM, turbulators, and thermal modules. While PV/T solar stills improved with DC blowers and NiCr heaters have demonstrated clear increases in thermal efficiency, two-effect humidifying distillation units have attained high water yields.

A further upgrade under investigation is radiative cooling, which increases water yield and efficiency. Some studies have concentrated on using double-glass solar stills with PCM to increase nocturnal productivity, hence greatly increasing water flow during evening hours. Other designs, including PCM and systems incorporating solar collectors, have shown continuous water output far beyond sunset.

Overall, constant developments in Solar still technology—including changes in absorber designs, PCM integration, hybridisation, and cooling techniques—have resulted in significant increases in thermal efficiency and daily water output, making solar distillation a more practical and efficient way for generation of clean water.

5. Conclusion

- In this detailed evaluation, researchers have thoroughly examined methods to boost the performance of both active and passive solar stills. Several types of solar stills, along with techniques for improving their efficiency, are included in the literature review.
- Painting the absorber plate with an amalgam of nanoparticles and black paint is a successful tactic. By expanding the contact area, productivity is maximised. Notably, CuO and Al2O3 nanoparticles are commonly used owing to their favourable thermophysical features and low costs.

Likewise, nanomaterials are prudent materials for storing energy that store energy throughout the day and releasing it at night.

- Nanomaterials can greatly enhance the thermophysical features of solar stills, such as the transfer of heat and thermal resistance. For thermal storage layers, phase change materials (PCMs) and non-phase change materials (NPCMs) have applications because they enhance the duration of operation by storing heat for use at a later time when solar radiation decreases. Solar stills with stearic acid and pinfins were the most productive PCMs studied.
- Another way to boost productivity is to add steel wool fibres (SWF) and PCM to the still basin. This leads to greater output during the day but lower productivity at night. The angle of the glass cover is very important, and the best distillate output occurs when it roughly resembles the latitude of the site. Energy efficiency is affected by internal irreversibility caused by fins in the storage unit.
- The results of the investigation demonstrate that the fluid velocity and water volume in the basin have an important influence on water generation. Furthermore, the addition of an external solar collector can supply the energy required for a continuous operation. Condensation rates can be further increased by using induced condensation via a thin layer of water or by overlaying the glass cover with a lightweight cotton cloth.

Conflict of interest

The authors declare no conflict of interest.

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