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Review Article

A Comprehensive Review of Solar Stills Performance and Design

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About Article

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ABSTRACT

The worldwide scarcity of potable water has increased significantly due to population expansion and the pollution of accessible water sources from anthropogenic activities. Solar stills are essential for supplying potable water via solar-powered distillation. Alterations, including phase change materials (PCM), nano fluids, and reflectors, markedly enhance heat retention and evaporation rates, leading to increased distillate production. Also, the efficacy of distillate production is significantly affected by design specifications, materials, and operational conditions. This paper delineates the passive and active designs, classifications of solar stills, single - effect and multi - effect kinds, and various improvements made to these types to augment yield, including heat storage, fins, reflectors, and collector types. Also, photovoltaic-thermal stills are encompassed in this review.

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1. INTRODUCTION

Water is necessary for both plants and animals to survive. Despite water covering 71% of the Earth, 97% is seawater, which is undesirable for human consumption because of its high salinity. Therefore, sea desalination can aid in resolving the water crisis. by supplying fresh water to metropolitan areas. In discussing the procedure of desalination, people suppose that it is a clean process to provide drinking water, but it is like many other industries and can impact the environment (Panagopoulos & Haralambous, 2020). The co-produced "brine" discharge stream has the potential to harm the environment due to its hyper-saline nature and potential for containing pollutants (such as NaOCl, $FeCl_3$, H_2SO_4, and $AlCl_3$) from the various processes in the desalination plant (Panagopoulos *et al.*, 2019). The energy needed for desalination systems is currently produced using fossil fuels, making them energy-intensive. Utilizing fossil fuels is linked to air pollutants and greenhouse gas emissions (GHGs) (Al-Shayji & Aleisa, 2018).

One of the most environmentally friendly desalination technologies is the solar still (SS), which may produce an independent water supply system with renewable energy and an easy-to-use system (Sharshir *et al.*, 2017). Solar stills primarily operate through the mechanisms of evaporation and condensation. The saline water within the solar still evaporates with solar power, and the production is collected as distilled water. Production and efficiency are two metrics that can be used to measure a solar still's effectiveness. The efficiency of a single-effect still is calculated by dividing the total solar energy received by the latent thermal energy of the condensed water. While overall efficiency indicates the entire day, instantaneous efficiency is defined for a short interval (usually 15 minutes). The quantity of water yielded daily per solar still area is known as productivity. Fundamental passive solar stills can only produce 2 to 5 L/m^2 per day; hence, one person's basic needs can only be met in an area of at least 1 m^2 (Kalidasa Murugavel *et al.*, 2008).

2. LITERATURE REVIEW

2.1. Overview of solar stills in desalination technology

Solar stills are a simple yet effective technology for producing freshwater by using solar energy to evaporate saline or brackish water, followed by condensation of the vapor. Their low operational cost, minimal maintenance requirements, and independence from fossil fuels make them particularly suitable for rural and arid regions (5). Unlike reverse osmosis or multi-stage flash distillation, solar stills require minimal technical expertise, making them ideal for decentralized water supply in developing areas. However, their relatively low productivity compared to conventional desalination systems remains a major limitation, driving the need for performance enhancement through improved design and operational strategies.

2.2. Fundamental principles of solar still operation

Solar stills operate on the basic thermodynamic principle of using solar radiation to heat water, which evaporates and subsequently condenses on a cooler surface. The main influencing factors include solar intensity, ambient temperature, water depth, and thermal losses (9). Single-slope and double-slope basin-type stills are the most widely studied configurations, with variations in geometry, glazing materials, insulation, and auxiliary heating methods aimed at maximizing evaporation and condensation rates.

2.3. Comparative studies and global experiences

Field studies across various climatic zones have reported significant differences in solar still output. In arid climates such as the Middle East, daily yields can reach 4–6 $L/m^2 \cdot day$ for optimized designs, whereas tropical climates often report lower yields due to higher humidity (17). Comparative analyses reveal that multi-effect stills and hybrid configurations consistently outperform conventional basin stills in both productivity and efficiency.

2.4. Economic and environmental implications

Solar stills are environmentally benign, relying entirely on renewable solar energy and producing zero greenhouse gas emissions during operation. Economically, their viability depends on local conditions, initial capital cost, and freshwater demand. Life-cycle cost analyses indicate that integrating locally available materials and renewable heat sources significantly reduces the cost per liter, making them more competitive against conventional desalination in small-scale applications.

3. METHODOLOGY

This study employed a systematic review methodology to comprehensively analyze the performance and design aspects of solar stills. The approach involved a structured and replicable process to ensure transparency, accuracy, and reliability of findings. The methodology was designed to capture both historical developments and recent innovations in solar still technology, covering a wide range of performance parameters, design variations, and application contexts.

The first stage involved defining the scope and objectives of the review. The study focused on various solar still configurations, including conventional single-basin designs, multi-effect stills, hybrid systems, and advanced modifications incorporating auxiliary heating or cooling techniques. Performance parameters such as distillate yield, thermal efficiency, energy consumption, water quality output, and cost-effectiveness were prioritized. To ensure relevance, the review concentrated on studies published between 2000 and 2025, thereby capturing both long-standing design principles and recent technological advancements.

The second stage consisted of a systematic literature search using reputable academic databases such as Scopus, Web of Science, ScienceDirect, and Google Scholar. Keywords and Boolean search strings were formulated to include terms like "solar still performance", "solar distillation design", "thermal efficiency of solar stills", "hybrid solar still", and "desalination using solar energy". The search also included grey literature sources such as conference proceedings, theses, and technical reports to capture industry-based innovations and experimental trials not widely published in peer-reviewed journals.

The third stage involved applying inclusion and exclusion criteria to filter the collected literature. Studies were included if they presented experimental data, simulation results, or detailed design analyses of solar stills. Articles focusing solely on unrelated desalination technologies, theoretical discussions without performance data, or studies lacking methodological clarity were excluded. A multi-stage screening process was conducted—first by title and abstract review, followed by full-text analysis for the final selection of materials.

In the fourth stage, relevant data were extracted systematically using a standardized extraction framework. The framework included key variables such as geographical location of the study, solar still type and configuration, climatic conditions, material specifications, operational parameters, performance indicators, and economic assessments. Where applicable, data were normalized to comparable units to facilitate cross-study analysis.

Finally, a thematic synthesis approach was applied to analyze the collected data. The selected studies were grouped according to solar still design type and performance improvement techniques. Comparative tables and trend analyses were developed to identify common patterns, technological gaps, and best-performing configurations. Findings were critically evaluated in light of climatic adaptability, material sustainability, and scalability for practical applications. This structured methodology ensured that the review offers a comprehensive, unbiased, and evidence-based understanding of solar still performance and design evolution

4. RESULTS AND DISCUSSION

4.1. Factors affecting solar still performance

Various criteria influence the productivity of solar stills, primarily associated with materials and designs. Incorporating phase change materials and nanoparticles in the design would improve thermal energy absorption and retention, increasing water productivity (Bouadila, 2023). The angle of inclination and the application of reflectors increase sun radiation on the solar still surface, hence enhancing evaporation. Environmental factors, including sun radiation and atmospheric temperature, profoundly impact the output of solar stills. Ultimately, the integration of sophisticated technology, such as photovoltaic panels and wind turbines, yields supplementary energy for operation and produces efficient water even under suboptimal weather circumstances (Lafta *et al.*, 2024).

4.2. Solar still

A solar still is a piece of machinery or equipment that uses solar heat to produce freshwater from saltwater. The idea behind it is comparable to the evaporation and condensation processes in The hydrological cycle. Seawater is heated into steam using solar stills, which collect and store solar energy (Fu *et al.*, 2021).

4.3. Passive solar still

A passive solar still is one where natural mechanisms for condensation and evaporation occur (Dsilva Winfred Rufuss *et al.*, 2016). The passive solar still operates on a straightforward principle. Solar stills absorb sunlight, which then heats the saline water. When the vapor hits the cold glass cover, it condenses into water droplets and falls to collect through gravity. The first solar still was created by Swedish engineers in 1872 to provide freshwater for mining sites in northern Chile (Delyannis, 2003).

4.4. Basic single - effect solar still

The single - slope, single - basin solar still (Figure 1) serves as the fundamental model of passive stills for comparison with more sophisticated designs. A multitude of research has been undertaken, varying in variables like the type of material, the inclination of the glass cover, the cooling method, the absorptive substance within the solar still, the composition of the input water, and the kind of basin liner (Rahbar & Esfahani, 2013). The selection of material affects efficiency, as evidenced by (Panchal, 2011), who performed experiments with different types of solar stills, .comprising aluminum and galvanized steel. The aluminum solar still produced a distillate production of approximately 3.8 L per m² per day, the 2.6 L per m² per day production of the galvanized iron kind, this discrepancy was ascribed to the superior thermal conductivity of aluminum. The angle of angle of the glass influences factors include distilled rate and immediate efficiency. Various researchers, however, arrived at divergent conclusions regarding the ideal predilection (Dsilva Winfred Rufuss *et al.*, 2016). Samee *et al.* (2007) developed a single - basin solar still and proposed that the optimal angle of the cover was 33.3°.

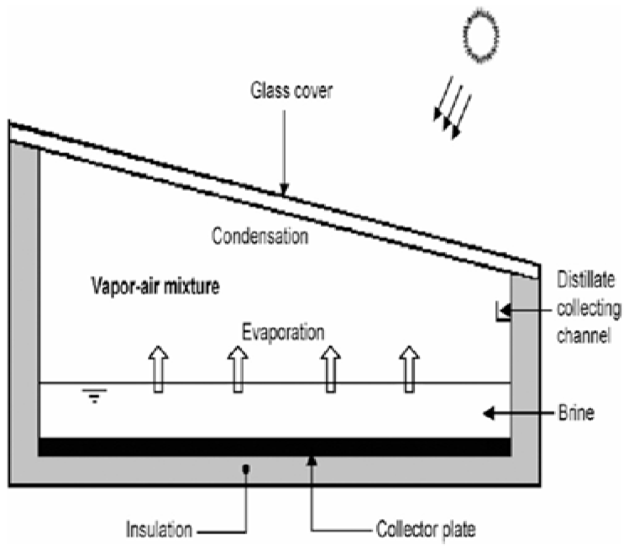

Figure 1. Single - basin single - slope solar still (Dev & Tiwari, 2009).

The immediate efficiency increases with the temperature of the supplied water. Medugu conducted a study on immediate efficacy related to radiation and the temperature of saline water, corroborating the experimental data by deriving theoretical predictions from the computation of energy balance equations for each element of the solar still (Feilizadeh *et al.*, 2010).

Li (2001) evaluated the efficacy of a single - basin solar still featuring a double glass cover, incorporating brine preheating and cover cooling mechanisms. An enhancement in performance was seen, attributed to an augmentation of the rate of evaporation, with an enhancement in the efficiency by as much as 25%.

The composition of the input water also influences the overall yield of the still. Vinoth Kumar and Kasturi (2008) conducted an experimental investigation utilizing diverse feeds, including tap water, saltwater, and dairy It was observed that yield was superior for both top water and seawater compared to the effluent. The disparity was ascribed to the suspended solid particulates in the industrial effluent.

The efficiency of single - basin stills is contingent upon the kind of basin liner employed. Badran (2007) performed trials utilizing two kinds of liners (asphalt and black paint) and discovered that the application of asphalt in the basin enhanced the yield by around 29%.

Several investigators have defined heat transfer coefficients and heat capacity in solar stills. Rahbar and Esfahani (2013) determined that the evaporation rate to convective heat transfer depended on the temperatures of the cover and saline water. Setoodeh *et al.* (2011) utilized computational fluid dynamics to model the heat transfer coefficient for solar desalination, concluding that the fresh water production rate remains largely unaffected by coefficients of radiative heat transfer, yet it is influenced by the input water and cover temperature.

4.5. Solar reflectors

One method to enhance the yield is to augment the quantity of solar power directed towards the still. This could be accomplished with a reflector. Tanaka (2010) Conducted experiments using a single - basin solar still equipped with external and internal reflectors (Figure 2). The productivity can be enhanced by tilting the exterior reflector backward in summer and forward during the other seasons.

Boubekri and Chaker (2011) conducted a numerical modeling analysis on the distilled yield of solar stills., incorporating both external and internal reflectors to achieve a productivity gain of 72.8%. The primary conclusions indicated the inclination for internal and external reflectors must be below 25°, while the ideal angle inclination for the cover varies seasonally between 10° and 50°.

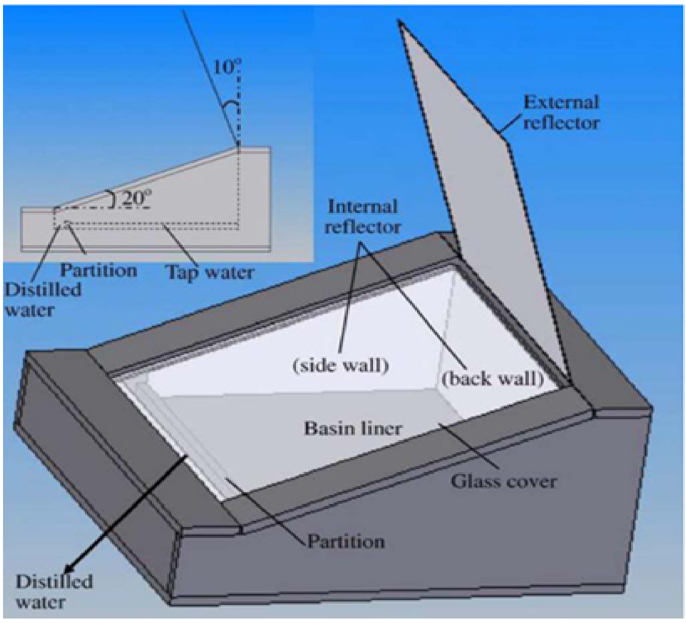

Figure 2. Single - basin single slope solar still with reflector (Tanaka, 2010)

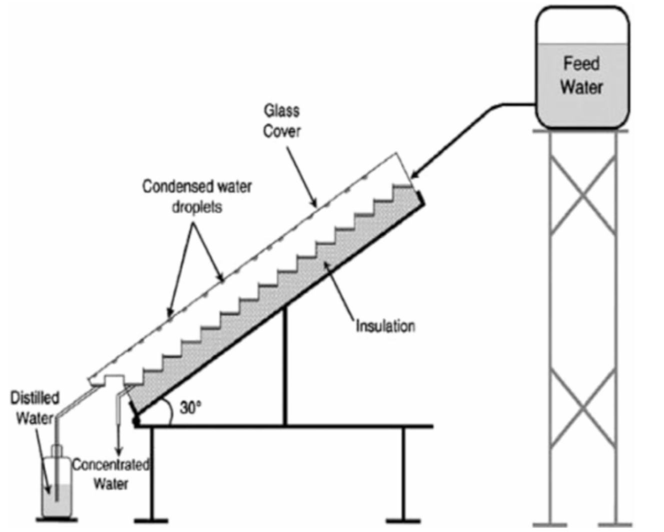

Figure 3. Single basin single slope stepped solar still (Rahim *et al.*, 1995).

4.6. Wicked and stepped-basin solar still

Alternative methods focus on enhancing mass and heat transfer in the solar still to improve the distilled yield. The implementation of wicks and stepped basins facilitates the retention and distribution of evaporating water, hence enhancing the rate of evaporation. This method has primarily been employed in single - basin stills, as illustrated in Figure 3. Numerous research investigations have been conducted about Thermal energy storage and exergy assessment in a stepped solar still (Dsilva Winfred Rufuss *et al.*, 2016).

Aghaei Zoori *et al.* (2013) performed a comparative analysis of exergy and energy efficiency in a stepped cascade solar still (Figure 4), reporting the greatest energy efficiency is 83.3%, whereas the maximum exergy efficiency is 10.5%. Energy and exergy fluctuations were determined to be exactly proportional to sun irradiance and the temperature of the inlet water. The low exergy efficiency indicates significant exergy destruction and a missed opportunity for meaningful production; this loss was mostly ascribed to the absorption plate, which was identified as a potential area for enhancement (Aghaei Zoori *et al.*, 2013).

Mahdi *et al.* (2011) designed a tilted wick solar still and attained around a 53% enhancement in daily efficiency utilizing a charcoal wick. Wicks and stepped evaporators can enhance production by 20% to 53%.

4.7. Fins

Fins at the basin of a solar still improve efficiency by augmenting the heat transfer rate from the basin to the saline water (El-Sebaii *et al.*, 2015). Velmurugan *et al.* (2008) conducted a study on a modified single - basin solar still (Figure 5) and discovered that yield raised by 45.5%, 15.3%, and 29.6%, for fins, sponge, and wick respectively.

Omara *et al.* (2011) performed a series of studies in conventional, corrugated, and finned stills. The still with fins demonstrated a 40% enhancement in production, but the corrugated still exhibited just a 21% increase compared to a conventional

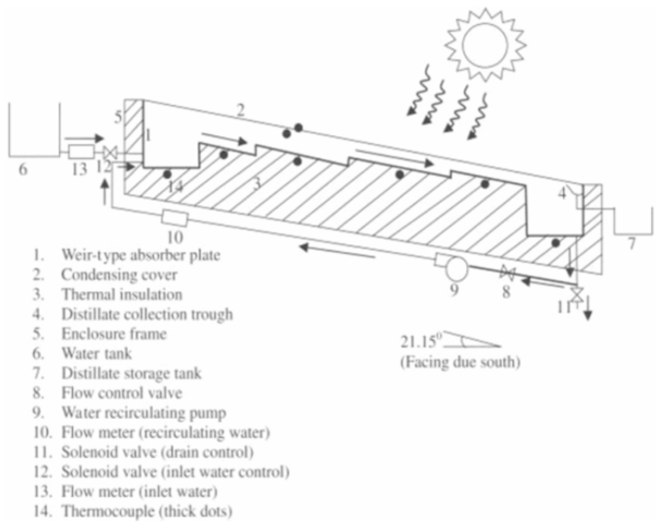

Figure 4. Single - basin single - slope stepped solar still with weir type absorber (Aghaei Zoori *et al.*, 2013).

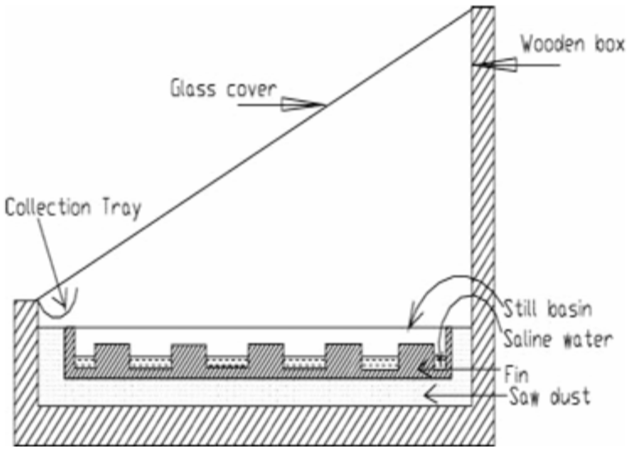

Figure 5. Single - basin single - slope solar still with fin (Velmurugan *et al.*, 2008).

still. The studies indicated that the efficiency of a finned solar still improve with the height of the fin and decreases with its thickness., but an excessive number of fins may reduce output (Dsilva Winfred Rufuss *et al.*, 2016).

4.8. Heat storage

An alternative method to enhance performance is thermal energy storage. A thermal storage media captures energy during maximum sunlight hours and subsequently emits heat when radiation diminishes. The solar still may therefore remain operational after sunset. Diverse materials have been employed to accomplish both sensible and latent heat storage (Dsilva Winfred Rufuss *et al.*, 2016). Energ *et al.* (1996) employed a black - painted aluminum sheet positioned just beneath the surface of water, nighttime output achieved an efficiency of 47.2%. Abdulhaiy placed paraffin wax (as PCM) underneath the basin in a stepped type solar still. The findings indicated that efficiency was approximately 61% and the yield was roughly 4.9 liter/m² per day (Radhwan *et al.*, 2005).

4.9. Unconventional shapes

The conventional solar still has rectangular dimensions and a trapezoidal shape in height. Researchers have proposed various configurations of passive solar stills, as will be explained below (Rubio-Cerda *et al.*, 2002).

4.9.1. Triangular stills

Numerous scholars performed multiple analyses of triangular solar stills, including parametric analysis, thermal analysis, and exergy analysis. Ahsan *et al.* (2014) performed a parametric analysis on a passive triangular solar still (Figure 6) by altering the water depth and several meteorological conditions. The depth of water was found to have an inverse effect on daily production. Siddula *et al.* (2022) conducted experiments on a triangular-slope polypropylene solar still and a single-slope solar still to study the effect of cap shape on productivity. The variable was water mass. The results showed that the brine temperature in the triangular-slope solar still was 6.8% higher than in the single-slope solar still, which means an increase in the productivity.

Figure 6. Single basin lengthy triangular solar still (Ahsan *et al.*, 2014).

4.9.2. Tubular stills

Tubular solar stills are designed to facilitate building (Dsilva Winfred Rufuss *et al.*, 2016). Yadav (2025) developed a tubular solar still consisting of 5 copper cylinders containing paraffin wax, which demonstrated a substantial enhancement in distilled productivity. The effect of saline water level on the efficacy of stills was investigated (PCM with 4 cm water depth) utilizing a modified tubular solar still (MTSS). The findings indicated a combined productivity of approximately 4.1 kg per m² for the conventional tubular solar still (CTSS) and 5.5 kg/m² for the (MTSS).

4.9.3. Hemispherical stills

Hemispherical covers have been engaged to enhance the quantity of solar energy harvested by the solar still. Arunkumar *et al.* (2012) study the effect of waterfalls on the glass cover in a hemispherical solar still. The results showed efficiencies of up to 42% and 34%, respectively, with and without waterfalls.

4.9.4. Multiple slopes

Li (2012) studied the effect of water depth on internal heat and mass transfer coefficients in a double-slope solar still and observed an increase in productivity of 3.07 liters/m² per day at a water depth of 0.1 meters.

4.9.5. Vertical stills

Arjunan and Sakthivel (2017) endeavored to improve the yields of solar stills by harnessing the heat energy present within vertical surfaces and to experimentally determining the optimal thickness of the vertical basin. The findings indicate that (i) the distilled yield of vertical basin solar stills surpasses that of conventional stills, (ii) heat loss from the inside wall surfaces to the outside wall surfaces is significantly diminished in vertical basin stills, and (iii) the optimal thickness of the vertical basin is 0.12 cm.

4.10. Multiple - effect passive solar stills

4.10.1. Multi - wick solar stills

Tiwari and Tyagi (1981) conducted a study on the effect of wicks on solar still production. It used multiple wicks made of wet black jute cloth. An increase in solar radiation absorption has been observed, which increased the solar still's efficiency to 34%, representing a 4% increase in efficiency compared to basin-type stills.

4.10.2. Multi - basin solar stills

El-Sebaii (2014) compared the effect of multiple basins on production and noted that production was higher in multi-basin solar stills than in single-basin solar stills due to the reduced heat loss in the lower basin due to the upper basin.

4.11. Active solar stills

Active solar stills incorporate supplementary components, like condensers, solar collectors, coolers, or other apparatus, to enhance performance. This equipment generally necessitates fans, and pumps, for its functionality. Consequently, in contrast to passive solar stills, active solar stills generally necessitate electricity (Dsilva Winfred Rufuss *et al.*, 2016).

Active solar water stills are often categorized into three kinds (Alwan *et al.*, 2024):

i. Elevated - temperature units: These systems entail linking the distillation device to an external solar collector.

ii. Preheated brine inlet methods: In this type, previously heated brine is introduced from multiple sources.

iii. Active night production: This technique entails supplying the basin with hot water once per day, utilizing either stored solar energy at night or harnessing waste heat from alternative sources.

4.12. Solar collectors

4.12.1. Flat Plate Collectors

Rajaseenivasan *et al.* (2014) conducted experiments on a solar still containing black gravel and cloth to increase the evaporation rate, combined with a flat collector, which observed a 60% higher productivity than the conventional model.

4.12.2. Evacuated tube collectors

Hemmatian *et al.* (2024) research comparatively evaluates the efficacy of different single - slope solar stills utilizing thermosyphon and pulsing heat pipe evacuated solar collectors, along with (PCM). The evaporator of the pulsing heat pipe system is attached to the evacuated tube, while the condenser is submerged in water to facilitate the passage of solar irradiance thermal energy. Paraffin wax serves as the phase change material, positioned at 2 filling ratios of 50% and 100% within the thermosyphon/pulsating heat pipe evacuated tube, to examine its effect on water production during periods of diminished sun irradiation. The thermal energy from solar radiation is stored in the phase change material and then transferred to the heat pipe system. The results indicate that the highest daily production achieved reached 2248 ml/m², representing a 40.7% increase in efficiency compared to conventional solar stills.

4.12.3. Solar ponds

Velmurugan *et al.* (2009) constructed a solar still integrated with a micro solar pond and performed experiments incorporating numerous alterations, including the insertion of sponges to the still. The findings demonstrate that the still using a sponge combined with a micro solar pond exhibits a superior condensate rate relative to alternative solutions.

4.12.4. Concentrating collectors

A cylinder-parabolic solar collector was utilized for heat collection, essential for distillation, and is integrated with the 4 stage still. The tested trays possess two distinct configurations: (V) and (Λ). It was found that the V-shaped trays are more efficient and economical than Λ-shaped trays, which need 2 collectors to give the same yield (Abdessemed *et al.*, 2018).

4.12.5. Air heater

To raise the temperature of the salt water in the basin more quickly, it has been proposed to combine an air heater with a solar still, thereby increasing the evaporation rate. Sampathkumar and Senthilkumar (2012) conducted experiments on a range of active solar stills and observed that adding an air heater to a solar still increased the distillate yield by 70%.

4.13. Photovoltaic - thermal stills

Hybrid solar distillers powered by photovoltaic cells have been developed. Sarkar and Bhattacharyya (2012) conducted a study on a solar still with photovoltaic cells, noting that the yield was three and a half times higher than that of conventional solar stills. Dev and Tiwari (2010) conducted an experiment on a solar still coupled with a flat-plate collector and a photovoltaic system and proposed a mathematical representation of the process. The primary conclusions of this study indicate the water's depth has a negligible impact on distillate yield, while significantly influencing the distilled yield of the active solar still, resulting in an increase in exergy efficiency of 2.6%. Singh *et al.* (2011) conducted a study on a double-slope solar still combined with a photovoltaic system (Figure 7), the production increased by 1.4 times compared to a single-slope solar still.

Figure 7. Single basin double slope hybrid solar still (Singh *et al.,* 2011).

4.14. Multiple-effect active stills

Elango and Kalidasa Murugavel (2015) experimented to examine the correlation between the depth of water and yield in a double - basin solar still. The findings indicated that the double basin produces a greater quantity of distillate solely when the depth of water is sustained at precisely 1 cm. The studies and improvement in multi - effect solar stills have incorporated solar stills with evacuated tube collectors, solar collectors, and parabolic reflector tube collector for solar water heating. Nishikawa *et al.* (1998) developed a solar desalination system that incorporates a solar collector with 3 effects for the purpose of desalinating seawater. The optimum freshwater produced was 9.44 L /m² per day.

The distilled yield of multi - stage solar stills is affected by several climate variables and environmental conditions. Elsafty *et al.* (2008) developed solar stills utilizing a parabolic reflector tube absorber. The work examines the impact of numerous factors, including ambient temperature, sun intensity, reflectivity of the reflector material, reflector aperture area, wind velocity, and the area of evaporation on production. The principal findings of this study indicate that condenser emissivity, wind velocity, condenser thickness, and depth of water are inversely correlated with distilled yield, while sun intensity, ambient temperature, and area of evaporation are directly proportionate to production.

5. CONCLUSION

Solar stills facilitate solar-powered desalination by fundamentally basic principles, wherein solar energy directly induces the water evaporation. Nonetheless, the objective of deploying solar stills on a commercial scale continues to be unattainable mostly due to their restricted production capacity. Researchers are actively exploring various advances in solar stills, focusing on operating variables, geometry, process setup, and materials for successful implementation.

Fins and corrugations are alternative methods to alter the geometry of solar stills, hence improving heat transfer and performance with significant efficacy. These improvements may encompass carefully selected materials to facilitate thermal energy storage, boost optical absorption, and provide insulating qualities. The most significant improvement in solar still efficiency is achieved through multi-effect and active methodologies. The primary factor hindering increased productivity in solar stills is solar energy absorption for evaporation of brine and heat loss for condensation. Various forms of solar energy collectors can be utilized to improve efficiency, involving evacuated tubes, solar ponds, and flat plate collectors. Notably advantageous among these is the solar still integrated with a solar pond, which increases production by around 80% compared to traditional stills.

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