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Research Article

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A Comprehensive Study on the Design and Performance of Solar Stills: A Review

Mital G Patel[1,2], Ruchir Parikh[3], Piyushkumar M Mistri[4], Hetal I Chaudhari[5,6], Raj Kumar Satankar[7]

[1]Research Scholar, Department of Mechanical Engineering, Gandhinagar University, Gandhinagar, Gujarat, India.
[2]Assistant Professor, Government Engineering College, Modasa, Gujarat, India
*** Corresponding Author Email:** mita2l@gmail.com-**ORCID:** 0009-0001-5751-9925

[3]Assistant Professor, Department of Mechanical Engineering, Gandhinagar Institute of Technology, Gandhinagar, Gujarat, India.
Email: ruchi2r@gmail.com-**ORCID:** 0000-0002-5247-6723

[4]Assistant Professor, Government Engineering College, Modasa, Gujarat, India
Email: mistr2i@@gmail.com- **ORCID:** 0000-0003-4949-0357

[5]Research Scholar, Department of Mechanical Engineering, Gandhinagar University, Gandhinagar, Gujarat, India.
[6]Assistant Professor, Government Engineering College, Modasa, Gujarat, India
Email: heta2l@gmail.com-**ORCID:** 0009-0007-5757-9593

[7]Associate Professor, Poornima College of Engineering, Jaipur, Rajasthan, India
Email: satanka2r@gmail.com-**ORCID:** 0000-0002-5247-5489

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Abstract:

Even though earth possesses a considerable amount of water (approximately 1.4 billion km³), only a fraction of 1% is freshwater resource for industrial, drinking and agricultural purposes. This reveals the need for effective water management and desalination technologies such as solar stills. In the recent years there has been increasing interest in solar stills, mainly due to their relatively simple, inexpensive and effective operation with desired properties in remote and arid locations. The efficiency of solar stills depends on several factors including solar radiation availability, environmental conditions (air temperature, wind speed, humidity), design or operational variables (surface tension, shape and style of top cover, water depth, condensing cover material), deployment of improvements, and effectiveness of the condensing process. Recent literature indicates that by utilizing nanofluids in solar distillation a considerable opportunity exists to improve the performance and efficiency of solar desalination systems. The emphasis in this review is on studying these parameters and their impact on the efficiency of the Solar Still.

1. Introduction

Water that is safe and easy to get is crucial for public health, whether it is used for drinking, cooking, or growing food. Global water (in its various forms like ocean, glaciers, rivers, lakes, etc.) reserves total 1.386 billion cubic kilometers. The largest component of our water cycle is the seas which contain approximately 97.5% [1] . The remaining freshwater 2.5 % (35 million km3), including atmosphere, surface water, polar ice, and groundwater, comprises the total quantity of freshwater. Only 0.06% of the freshwater that is available is readily accessible; the remainder is made up of wetlands, groundwater, and frozen polar ice caps or glaciers. Because they are used for industrial and drinking water production, fish farming, shipping, and irrigation, lakes and rivers are important to the environment worldwide. Additionally, lakes and rivers contain 0.3% of the freshwater on Earth. Only 2% of the liquid freshwater on Earth's surface is found in rivers, whereas 87% is found in lakes [2]. That suggests that just roughly 0.014% is directly accessible to humans and other animals [1].By 2030, the WHO expects the universal access of safe and affordable drinking water to all people. Nevertheless, following all significant efforts, 6 billion individuals (who represent 73 percent of the entire world) utilized safely managed drinking tap water offers in the year 2022, which are accessible when required and not contaminated. The rest of the 2.2

billion population was not able to access safely managed services. Geographic, sociocultural, and economic differences between rural and urban regions, along with rural-urban or within-urban, exist to this day with residents of low-income, informal, or illegal settlements generally having less access to better drinking water sources than their counterparts. Moreover, it is estimated that in 2050, two-thirds of the world population will be facing extreme water deficiency. Thus, the current level of development will have to grow effectively in order to reach a desired objective of safe drinking water to all [2]. WHO says that cholera, diarrhea (which kills over 1.4 million people a year), dysentery, hepatitis A, typhoid, and polio are some of the diseases that can be spread by dirty water and poor sanitation [3]. Inadequate or improperly administered water result in the exposure of individuals to preventable health risks. Conventional treatments may be costly to run and dispose of hazardous materials such as chemicals, pesticides, heavy metals, and sediments; they may also be inefficient and have high energy costs; additionally, they may need trained personnel to operate. These challenges prompt us to employ easy, affordable and sustainable methods to provide fresh water to all societal segments. A technology that effectively and sustainably uses the sun's power to provide clean water is found in the field of renewable energy [4]. A solar desalination system quickly transforms salty or contaminated water into clean water by capturing solar energy.

2. Solar energy and desalination

Typically, the electromagnetic radiation radiated by the sun is known as solar radiation. There are many types of technology that can capture solar radiation and convert it into useful forms of energy such as heat and electricity. Some methods, such as reverse osmosis, utilize desalination processes that require electricity, and that electricity is derived from fossil fuels, causing harm to the environment and using up non-renewable energy. In contrast, sustainable and safe solar desalination techniques are solar stills, multiple-effect distillation, and multi-stage flash distillation[5].

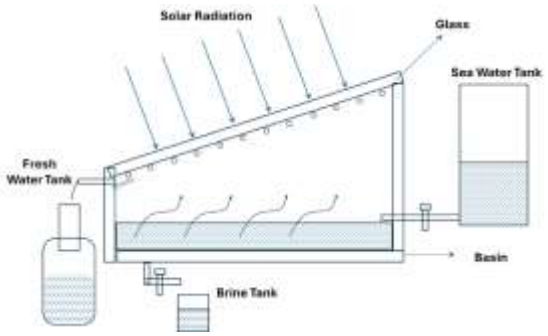


Figure 1: *Solar Still [6]*

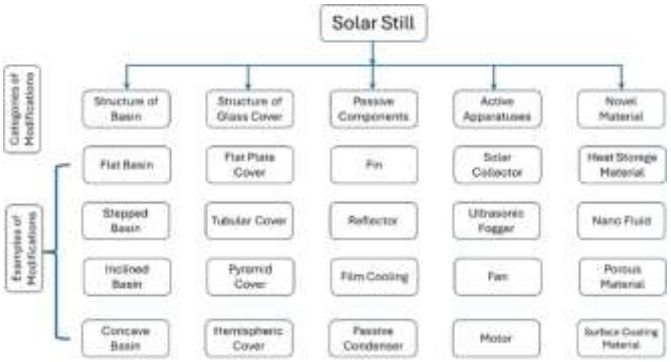


Figure 2: *Various Types of Solar Stills and Modifications*

A technique for purifying water is solar distillation, which harnesses the sun's warmth to evaporate contaminated water and subsequently gathers the purified vapor to create clean water. As seen in **Figure 1**, the apparatus used for sun distillation is called a solar still [7]. This technique is especially helpful in regions with dry, arid and desert climates that experience severe water scarcity and in isolated locations with limited access to potable water, even the water from bore wells may not be fit for human consumption when traditional purifying techniques are unavailable. An easy, affordable, and environmentally friendly

approach is solar distillation. Their limited production, however, puts them at a disadvantage.

3. Classification of solar distillers

Arab alchemists employed the first still in 1551, and Charles Wilson created the contemporary typical still in 1882 [8]. Since then, researchers have made numerous changes and improvements. As seen in **Figure 2**, there are numerous varieties of solar stills in use today.Since the invention of solar stills, fewer communities have begun to use them. Despite extensive investigation by numerous researchers, solar stills are still not widely used or commercially accessible for average homes and businesses. The solar still must be removed from the lab and brought to the public utility. Finding the ideal solar still design for home and commercial use is really challenging. Comparing various solar stills from an application and financial perspective is therefore necessary. Numerous researchers have produced extensive studies of solar stills in order to comprehend technological advancements and to examine and contrast thermal performance, including solar still yield.

4. Factors influencing solar still efficiency

An analysis of different solar still models, including their benefits and drawbacks, offering useful perspectives for future exploration and innovation, have been made by many researchers [9–12]. They have suggested that the choice of a solar still design is based on location, water quality, materials available, and cost. The performance is determined by meteorological and design parameters, which need to be optimized for improved productivity. According to Kaviti *et al.* (2015), inclined solar stills can boost water's surface area while maintaining a minimum depth, which increases productivity [13]. The authors talked about the significance of design elements including water depth, absorber plate size, glass inclination, and free surface area of water as well as the use of wicking materials to improve the water evaporation rates and residence times. Kabeel *et al.* (2012) [14] carried out a theoretical and experimental study on the impact of increasing the width and depth of the trays on the performance of the stepped still. A stepped solar still facilitates maintaining sufficient water depth in spaced solar stills to ensure productivity [15].The primary drawback of solar energy is the need for sunshine in order to be used. In the area of renewable energy, phase change materials, or PCMs, are important materials that can absorb energy when the sun is shining, then release it after sunset as needed so the solar energy can work without sunshine. [16]. A comprehensive analysis of all solar still-related instruments was carried out by D. Dsilva *et al.* (2016), who covered subjects like the range of designs, performance-enhancing techniques, and economic models, as well as potential avenues for further research [17]. Phase change materials (PCMs) and nanocomposites are examples of novel materials that the authors pointed out could further enhance performance in upcoming applications [18]. The impact of stepping solar stills, cords, wicks, absorber shapes, and rotating components on productivity was investigated [19]. Katekar *et al.* (2020) provided a survey of different designs of solar stills, emphasizing the energy efficiencies and domestic and industrial applications [20]. They have assessed various modifications, including reflectors, phase change material and different types of absorbers. Additionally, by using solar water heaters, reflectors, condensers and a concentrator, and by using PCMs and nanocrystals, the performance can be enhanced [21]. A multi-stage solar still performed much better [22].In conclusion, an assessment between solar still designs emphasizes the optimization of climatic, operational, and design factors. Design improvements and novel materials, such as PCMs and nanocomposites, may lead to improvements in efficiency and productivity.

5. Review of solar still based on design

5.1 Single Slope Solar Still.

The basic attributes of the solar stills are their simple design and inexpensive production. The single-basin solar still is the simplest solar distillation device [23]. It is simple to make, simple to use, and simple to maintain. One of the major downsides of this design is that it has a low yield, which depends on the season, geographic location, and intensity of solar radiation.

5.1.1 Parameters Affecting Still Productivity

Ithape *et al.* (2017) [6] and Ali. F. Muftah *et al.* (2014) [12], analyzed the factors of climate and design variables on output performance of a solar still. The study emphasizes the importance of solar radiation intensity, ambient temperature, wind speed, relative humidity, water depth, insulation and material angle tilt of condensing cover. They reported that increased solar radiation intensity and ambient temperature, support an increase in performance. Wind speed and relative humidity as well are important factors with optimum conditions favoring increased output. Furthermore, the type of cover for condensing with thickness, as well as insulation and angle have a major impact on productivity. Lastly, the volume of water in the

basin is important as it affects the overall energy balance and, ultimately, the efficiency. For example, a simple basin-type still which is discussed by Mehta *et al.* (2011) [24] is made up of a glass plate on top of the basin, a GI box housing in a wooden enclosure insulated with thermocol to reduce heat loss and increase the absorption of solar energy. They have obtained efficiency of 64.37%.

5.1.2 Effect of Water Depth

Raj *et al.* (2017) noted that as water depth increases, the distillation yield drops. This is because the methods used to transfer heat, including evaporation, radiation and convection from the water to the glass cover, become less effective when the water depth is deeper [25].

5.1.3 Effect of Reflector and Its Tilt Angle

Ravindra *et al.* (2023) [26] investigated the impact of a reflector on the performance of a single slope solar still. It was observed that the distillate output decreased under higher water level in the basin, and the optimum tilt angle for the reflector was at 60° and demonstrated that the still with the reflector outperformed the still without the reflector by 24.2%.

5.1.4 Stills Integrated with Sand Bed.

Employing sand beds (black sand at a 1 cm height), internal reflectors, and cooling coils drastically enhanced the performance of stepped solar stills. As a result, the thermal efficiency increased and the cost of freshwater production was lowered. To improve the performance of a solar still and reduce its payback time, Krishnan et al. (2023) conducted an investigation into the performance of heat absorber materials, such as sand, dirt, and paraffin wax [27]. Improvement in daily efficiency of 56.56% with heat absorber material have been observed.

5.15 Modified Absorber Bed

An in-depth study on a developed model of a single basin solar still, called the trays solar still (TSS), to enhance the effectiveness of evaporation was conducted by A. S. Abdullaha *et al.* (2020) [28]. The TSS includes internal trays that enhance the evaporative surface, along with reflectors, to increase the solar energy input. The findings revealed that, at specific water levels, the TSS, without reflectors, shows a daily productivity of approximately 1.5x greater than a CSS system. This productivity was also increased by 95% when both external and internal mirrors were included with the TSS system. The study has also shown that TSS produced fresh water at a lower cost when compared. A theoretical model was developed to estimate the performance of the solar stills. The findings are verified using experimental data, and they demonstrate a good agreement with a variance of roughly 7–10%. Atteya *et al.* (2023) work explored how using internal reflectors and sand beds can improve the performance of stepped solar stills (SSS) [29] as shown in **Figure 3**. Similarly, production of tray solar still improved by Taieb *et al.* (2023) [30]. The largest increase in cumulative production, which was 105% more than CSS, was achieved at a height1 cm of the sand bed using black sand. The daily freshwater yield for the CSS, TSS, yellow STSS, and black STSS increased because of the internal reflectors, which further improved the TSS's performance.

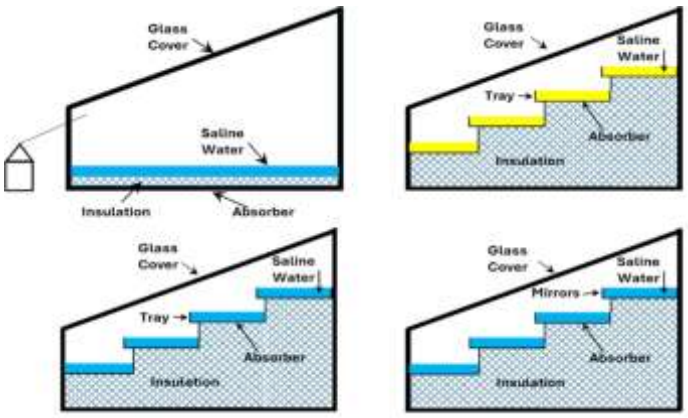


Figure 3 *Stepped Basin Solar Still with Sand Beds, Internal Reflector [29]*

Emad *et al.* (2023) [31] have used wire mesh as the absorber with pulse flow of water and obtained 102% enhancement in the yield with two layers of wire mesh. The solar distillation system's thermal efficiency and productivity are greatly increased by the addition of a honeycomb structure, which reduces reflectivity and improved heat absorption which has efficiency of 37.71% [32]. Djaballah *et*

al. (2023) proposed some plastic fins in solar stills to evaluate surface tension's influence [33]. Although plastic has a lower thermal conductivity than metals, plastic fins are a useful and low-cost alternative for solar distillation. The findings indicated that plastic fins of 0.5 cm in diameter are optimal for improving production in solar stills.

5.1.6 Increase in Condensation Surface Area by Incorporating Water Jacket.

According to an article by Vigneswaran *et al.* (2023) [34], the authors developed a novel method to improve the productivity of passive solar stills (PSS). Employing water jackets on the sidewalls of passive solar stills drastically enhances augmenting productivity, thermodynamic efficiency and energy efficiency for passive solar stills.

5.1.7 Preheating the Feed Water

Devices for preheating, such as solar cookers and geothermal energy sources, show a notable increase in the productivity, that use renewable energy sources. Solar cookers were very good results in achieving higher temperatures of the fluid [35]. Solar thermal energy storage technology equipped solar cookers can be used for preheating of water at night also [36]. The study Angappan *et al.* (2023) presented a new configuration where a solar still is combined with a solar box cooker, which circulates saline water between them to expand the absorption area and elevate water temperature [37]. The active solar still enhances production by 41% and increases efficiency by 27.6%. Verma *et al.* (2023) [38] have proposed a novel concept of integrating geothermal energy with solar stills using a coaxial borehole exchanger. A transient as well as steady-state heat transfer models were developed and validated and were checked against modelled and experimental data finding a maximum deviation of 14.4%.

5.1.8 Integrated with Various Solar Collector

Trough and disc types of parabolic reflectors distinctly amplify success for cooking [39,40]. Farghaly *et al.* (2023) looked at how adding evacuated tube collectors (ETC) and parabolic trough reflectors (PTC) to a basic single slope solar still can make it work better [41]. The experimental setup consisted of three scenarios: a conventional still, a still fitted with ETC, and a still with both ETC and PTC, productivity improved with both evacuated tube collectors and parabolic trough reflectors by 112.57%.

5.1.9 Absorber with Nano and Phase Change Material Materials

Metal oxide nanoparticles are commonly used in a variety of industries due their unique properties, such as high absorption capacity for radiation, high thermal conductivity, photocatalytic capabilities, biocompatibility, antibacterial effects, transparency, and high isoelectric point [42]. Eswaran *et al.* (2023) investigated the performance of solar stills with ETC and analyzed the effect of introducing nanoparticles (CuO, Al_2O_3, and ZnO) into the distillation process [43]. The desalination was made more effective with nanoparticles.

The productivity of modified solar stills was measured experimentally by A.S. Abdullah *et al.* (2023) [44] who also looked at how temperature and solar radiation affected. The MSS has undergone a number of tests, such as those that use an external condenser, internal and external reflectors, PCM-Ag, and a copper coil for water heating. The stability and uses of inexpensive carbon quantum dot (CQD) nanofluids to improve the efficiency of solar stills were covered in a different study by Chen *et al.* (2023) [45]. The CQD nanofluids demonstrated exceptional stability in the presence of numerous salt ions, organic matter, and a range of NaCl concentrations. The nanofluids also showed very good optical properties, absorbing nearly 100% of incoming solar energy at 10 vol %. These CQD nanofluids also provided significant increases in water productivity by 57.9% and energy efficiency by 34.23%.A study by Parikh et al. (2025) [46] examined efficiency improvements for solar stills using a cooling glass cover and hybrid nanomaterials coating (Fe_2O_3 and Cu_2O) through the use of water sprinklers has shown a yield increase of 34% with cooling and 28% without cooling, thus these management methods significantly improved the overall efficiency.

5.1.10 Absorber with Wick Materials

Abdullah *et al.* (2019) evaluated the performance of a rotating wick solar still with various operational conditions, including different ON and OFF periods for the rotation of the wick and the implications of nanofluid use [47] as shown in **Figure 4**. The research showed that the average performance was maximized with 30 minutes OFF time. The performance improved even further with nanofluid, that is efficiency increases to 84%. A study by Abdullah *et al.* (2022) conducted an experimental investigation of using wick-finned absorbers and nano-enhanced PCM to enhance the performance of TSS [49]. This study analyzed the

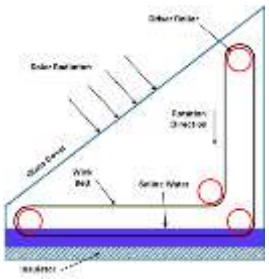


Figure 4: *Rotating Wick Solar Still [47]*

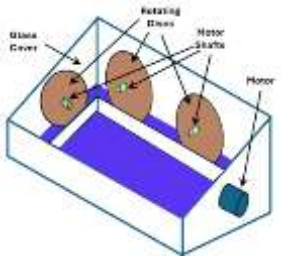


Figure 5 *Rotating Disc Solar Still [48]*

effectiveness of TSS with flat and finned absorbers to improve the heat transfer between the absorber surface and saline water. The effectiveness of TSS was compared not only with phase change materials but also with copper oxide nanoparticles, reflective mirrors, and jute wick materials to further improve performance. The results indicated that use of finned TSS improved the productivity.The efficiency of a rotating wick solar still (RWSS) under various design and operating conditions was investigated by Abdullah *et al.* (2021) [50]. Additionally, they investigated the potential for concentrating solar energy into the RWSS system through the use of internal and external mirrors. Similarly, when utilized alongside a thermal energy storage system and reflectors, rotating discs in various configurations, such as flat, finned, and corrugated, as shown in **Figure 5**, have demonstrated a considerable improvement in performance [48]. Younes *et al.* (2021) [51] investigated the effectiveness of novel absorber designs in tilted wick solar stills, as shown in **Figure 6**, including half barrel and corrugated absorbers. A phase change material (PCM) in combination with CuO nanoparticles was also used to examine the performance. The study found that adding PCM with nanoparticles and altering the absorber design of wick solar stills significantly improves their performance. Out of all the designs that were examined, the CWSS performed the best.

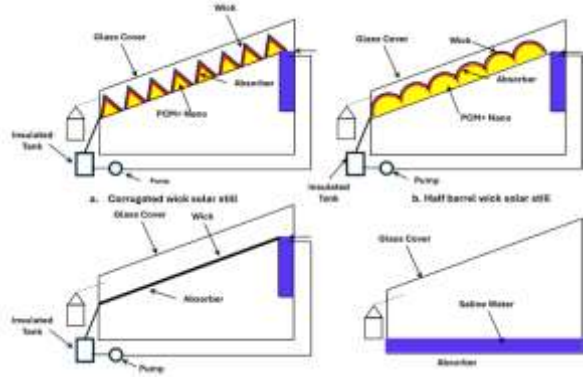


Figure 6: *Tilted Wick Solar Stills with Various Absorber Configurations [51]*

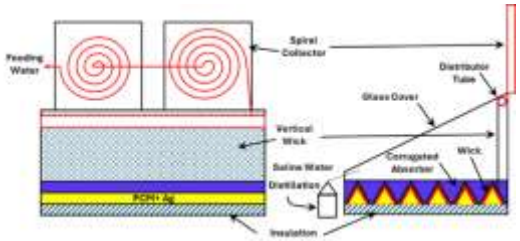


Figure 7: *Corrugated Wick Solar Still [52]*

5.1.11 Combination of Several Techniques

Abdullah *et al.* (2023) reported the results of an experimental study that compared an MSS and a CSS in comparable weather conditions [53]. A nano-sized PCM used to improve thermal efficiency and preheat the feed water, an inner reflector to direct more sunlight toward the water's surface, and spiral copper heating coils to absorb and transfer heat to the water were among the improvements made to the MSS. The authors found that the MSS, with all improvements, significantly increased productivity and thermal efficiency. Moreover, Abdullah *et al.* (2023) investigated a CWSS modified with an external spiral copper water heating coils and a Nano PCM, as shown in **Figure 7** [52]. They concluded that the modified CWSS was a productive and efficient as well as feasible. Elbara *et al.* (2020) [54] carried out an experimental study to improve hybrid solar distillation systems. The results showed improvement in the temperature of saline water and freshwater production with the combined use of black steel wool fibers and heating the saline water. In another similar study [55] authors examined the use of titanium oxide and black dye as a coating to improve the efficiency. Their results at 20% and 40% concentration showed a 11-18 and 20-23%

increase in efficiency, respectively. Wax filled rods were integrated by Dumka *et al.* (2024) [56], the cumulative yield of MSS was 12.8% more than that of CSS.

5.1.12 Cogeneration System

A new cogeneration system developed by Yari *et al.* (2016) [57], which consists of a semi-transparent PV module to produce electrical generation and an ETC to preheat the basin water, which increases the overall system efficiencies. A concentrated solar-PV-thermal (CPVT) integrated system for concurrently producing electricity, cooling, and desalination was proposed by Yadav *et al.* (2023) [58]. In conclusion, solar stills are attractive for their simple structure and inexpensive manufacturing methods, though several improvements have been suggested to boost their effectiveness and output. Environmental factors like wind speed, ambient temperature, solar intensity, and the choice of condensing cover materials have been shown to have a significant impact on performance. Performance can be successfully increased by new innovations like rotating discs, internal trays, reflectors, and the use of nanofluids. The incorporation of geothermal energy, evacuated tube collectors, parabolic trough reflector designs, and novel cogeneration designs have been explored. Further design changes including, using phase change materials, jute wicks, and heat absorbing materials such as paraffin wax or sand, have demonstrated improvement. Recent advancements and experimentation modifications, such as natural exterior reflectors, spiral heating coils, and porous materials, show substantial improvements. Furthermore, assessments of solar still components, integration of solar panels with solar still systems, and assessments of alternative cogeneration systems demonstrate the feasibility of the integrated sustainable water and power generation option.

5.2 Double Slope Solar Still

One advantage of the double-slope solar still (DSSS) is that it effectively doubles the condensing surface without causing significant complexity to the system's construction [59]. Compared to single-slope solar stills, the DSSS can be built economically with common available materials. Maintenance and operation are similarly simple. Another downside is its small production like the single slope. Most of the parameters which affect a single slope solar still will also affect a double slope solar still. Parameters can be modified, but care must be taken, because they can significantly increase complexity and cost. An example of such a modification is using hollow fins with circular cross sections, which has demonstrated good results [60].

5.2.1 Effect of Depth of Water

The influence of water depth and ambient temperature on the operations of a DSSS was examined by Babalola (2015) [61]. The DSSS used for testing purposes was designed from an aluminum basin and a tempered glass cover and was tested at an angle of 50 degrees. The authors examined a range of water depths and recorded ambient temperature during the testing and found that they had significant effects on the performance of the double slope solar still.

5.2.2 Effect of Glazing Slope

In addition to the thickness of the water, the angle of the glazing significantly influences performance [62]. The air gap at the interface between the glazing and the water also had a notable impact.

5.2.3 Increase in Free Water Surface Area

To maximize the surface area of free water in contact with hot air, T-shaped copper pieces were utilized [63]. The T-shaped copper pieces can also help to reduce the surface tension between water molecules for the water to evaporate more readily. Sibagariang *et al.* (2023) [64] investigated the effect of oil palm shell which hold heat and cheaper option. Raihananda *et al.* (2021) examined the design and performance of an affordable floating solar still system [65]. The authors built the prototype in which there was significant heat localization as evidenced by a significant temperature difference between the absorber surface and bulk water.

5.2.4 Effect of Glass Cover Temperature.

The problem with solar stills is that their cover glass gets extremely hot, which lowers the rate of evaporation [66]. Condensation can be improved by adding water cooling to the glass cover where a pump is used to flow the water [67], yet they require extra energy and might decrease the sunlight reaching the absorber plate.

5.2.5 Preheating the feed water

The water can be preheated with the solar collectors. With these modifications, the performance of solar stills can be significantly enhanced. The saline water can also be heated using evacuated tubular collectors fitted into a parabolic concentrator [68].

5.2.6 Combination of Several Techniques

An investigation into the architecture and

functionality of a dual-slope solar still using a mild hybrid energy system was conducted by Feria-Diaz *et al.* (2023) [69]. They investigated improvement in heat retention by using commercial PCMs. Despite PCMs increasing heat retention time, they did not reduce production costs. Metal oxide nanoparticles (TiO_2 + ZnO and TiO_2 + Al_2O_3) and feedwater preheating [70], hollow circular fins, internal sidewall reflector, and simultaneous thermoelectric heating and cooling system PCM [71], and with eutectic PCM, eutectic PCM combined with steel wool fiber, and nano-enhanced eutectic PCM demonstrate remarkable effectiveness [72].In general, the double-slope solar still has the potential to improve water yield by enhancing condensing area design modification and using new materials such as oil palm shells or PCM. The productivity of the system depend on many factors including: water depth, glazing slope and hollow fins are used; there effectiveness is vastly increased by using circular cross sections with some holes (Fin's side view); copper t- shaped pieces act as thermal store which both retain heat much better than other materials, and amplify evaporation rates. Other research with low-cost floating solar stills and hybrid energy systems has illustrated the possibility to enhance further efficiency along cost-effectiveness in terms of solar still columns.

5.3 Hemispherical Solar Still

One of the most efficient options for supplying fresh water in remote and rural areas is the hemispherical solar still (HSS). The efficiency of hemispherical solar stills is constrained, and many researchers have investigated methods to enhance the thermal performance of HSS. A comprehensive review article discusses the HSS presented by Younis *et al.* (2022) [73]. Recent advances in HSS design, performance, and cost analysis reveal the significance of this technology to a sustainable future. The review indicates HSS is suitable for creating freshwater. Research and development should continue to enhance cost-effectiveness and efficiency, which would support the case for HSS as a suitable option for sustainable desalination.

5.3.1 Modified Absorber bed.

The research conducted by Attia *et al.* (2021) looked into the influence of black-painted metal trays made from copper, zinc, and iron on yield and thermal performance of HSS [74]. The research showed that the incorporation of metal trays, particularly copper, positively influences the yield and thermal performance of HSS. Throughout the day, the hemispherical chamber stepwise basin can absorb more heat from direct sunlight [75]. The usage of a PV-powered electric heater improves performance when used with this type of still.

5.3.2 Absorber with porous materials

The use of natural inexpensive porous materials specifically dyed flax fibers, to enhance the productivity of hemispherical solar distillers was investigated by Kabeel *et al.* (2022) [76]. The research undeniably demonstrates that dyed flax fibers, black dyed flax fibers in particular, will substantially increase the productivity of HSS. This is a sustainable and cost-effective alternative to the more expensive productivity enhancements. Future work may examine the best fiber layers' thickness and the use of nanomaterials to flax fibers to further enhance the efficiency of distillation. Researchers have also examined combining the extension of hollow cylindrical fins that incorporate phase change materials (EHCF-PCM), arranged in a mutually conducive manner to the productivity privatization of HSS, as shown by Attia *et al.* (2022) [77]. They have reported that using PCM with the fins increased the efficiency of HSS considerably both day and night. They also reported the necessity of the number of fins and the distance/spacings of the fins. They concluded that using elongated cylindrical iron fins at different spacings was important and improved the overall productivity [78].

5.3.3 Integrated with the Sand Bed.

The use of outside reflectors and a vapor extraction fan significantly enhance performance, along with various types of sand beds at different heights that act as thermal storage elements [79].

5.3.4 Integration with solar collector.

The study by Dahab *et al.* (2023) investigated the integration of different numbers of EVT in two distribution categories: solely in the southern direction and all around the water basin perimeter [80]. The authors determined that incorporating EVT into a hemispherical solar still greatly enhances its efficiency, rendering it a viable option for water desalination.

5.3.5 Combination with Several Techniques

It was discovered that wick material, rear reflectors, external condenser, and fan integration, in addition to nanoparticles and phase change materials, were useful instruments for improving the performance [81]. Inverted solar collectors as heaters and semi-corrugated basins optimize the yield [82].The research on hemispherical solar stills (HSS) highlights various innovative enhancements, such as the incorporation of various innovative materials and designs, such as metal

trays, dyed flax fibres, natural porous materials, phase change materials and long, hollow, cylindrical fins that are packed with materials that change phases, which significantly improve their productivity and thermal efficiency. HSS is now a viable and sustainable freshwater production option because to these developments.

5.4 Pyramid Solar Still

Pyramid solar still operates effectively and provides a greater surface area for condensation compared to basin solar. This system is referred to as a pyramid solar still due to the fact that its upper cover takes on a pyramid shape. Because it offers a bigger evaporation area for the same basin area, comparing the pyramid solar still with the conventional and double slope, pyramid solar stills have higher productivity and efficiency [83]. By changing the cover angle, pyramid height, and other specific arrangements, productivity increased even more, but this also made it more complex [84]. Elgendi *et al.* (2023) conducted a study that sought to establish the most significant meteorological and solar still parameters in relation to pyramid solar still productivity. This task is not simple, as those parameters can depend on one another [85]. The research used data that described hourly measurements of wind speed, feedwater temperature, ambient temperature, and solar radiation from the experimental setup. The authors stated that the most important contributors to obtaining optimal performance and planning for placement of solar stills were these factors. Hammoodi *et al.* (2023) reviewed advances and developments in pyramid solar distillation techniques, focusing on contemporary improvements and new developments aimed at enhancing productivity and efficiency [86]. The authors highlighted the significance of many techniques, including wick materials, storage materials, and heaters and nanofluids to enhance the performance of a pyramid solar still. The results present important considerations for researchers and decision-makers to enhance the designs and performance of these systems.

5.4.1 Preheating the Feed Water.

A heating system may be integrated into a classic pyramid solar still to enhance its efficiency [87]. Integrating sensible and latent heat energy storage into triangular pyramid solar still configurations enhance efficiency dramatically [88,89].

5.4.2 Absorber with Nano and Phase Change Materials

Adding various nanoparticles to the basin water of a PSS can significantly increase its productivity [90]. Al_2O_3 nanoparticles being more effective than SiO_2 nanoparticles. Wicked still design increases the rate of evaporation to enhance still production [91]. The effectiveness of different wick materials has notably improved, comprising light cotton fabric, thick cotton fabric, jute material, and velvet material. A pyramidal absorber and corrugated absorber plate can also increase the evaporation surface area [92,93] as shown in **Figure 8**. A significant increase in yield has been observed with the corrugated absorber plate. Furthermore, performance can be increased of PCM combined with silver nanoparticles for thermal energy storage, external reflectors to enhance solar energy, an external condenser, and pyramidal absorber stills integrating with various wick materials.

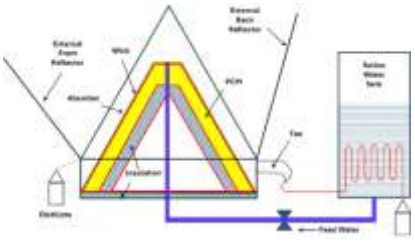


Figure 8 *Pyramid Solar Still with Pyramid absorber, mirrors, condenser, wick materials, and PCM [92]*

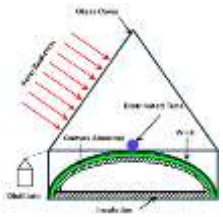


Figure 9 *Novel convex and dish absorbers in pyramid solar still [94]*

To understand the actions of water vapor and condensed water droplets in solar distillation, the chemical potentials of the temperature elements within a pyramid stepped basin solar distiller (PSBSD) were evaluated [95]. This study uses the Gibbs phase rule to establish a relationship between the experimental parameters, climate, and distiller design. The results show how crucial this strategy is for improving solar distillation methods.

5.4.3 Combination Several Techniques

Essa *et al.* (2022) incorporated a conical absorber to maximize the evaporation surface area through the inclusion of cotton and jute as the wick materials [96]. They also introduced an external mirror and a condenser. They also studied the

effect of a PCM with silver nanoparticles to enhance thermal storage and efficiency. The research underscored the promise of the MPSS as a more effective and affordable method of producing freshwater in rural regions and for moderately sized families.Based on novel convex and dish absorbers, various wick materials, and coatings using nanoparticles, an experimental investigation was conducted to study the performance of a pyramid solar still (PSS) designed by Omara *et al.* (2022) [94] as shown in **Figure 9**. The goal of study was to enhance production by maximizing the exposure surface area, evaporation, and minimizing water depth. The CDPSS, with the tweaks, operated better than PSS in reducing inlet water depth to air and can provide an economically feasible and sustainable approach for the desalination process in seawater. Areas for future work may include optimizing nanoparticle concentration and developing theoretical models for industrial use.

5.4.4 Absorber with nano materials

For the purposes of modelling and optimizing a pyramid solar still and predicting its thermal efficiency under the presence of different nanoparticles and environmental aspects, Farouk *et al.* (2022) used response surface methodology (RSM) [97]. The objective of the research was to increase the productivity of the pyramid solar still by investigating the effect of solar intensity, ambient temperature, wind speed, and the addition of nanoparticles including copper oxide (Cu_2O), aluminum oxide (Al_2O_3), and titanium oxide (TiO_2) on the performance of solar still. The study concluded that the RSM is a useful technique in evaluating performance in the presence of nanoparticles. Moreover, using Cu_2O nanoparticles is especially beneficial for enhancing productivity. The advancements in pyramid solar still technology significantly enhance productivity and efficiency in freshwater generation. with advancements such as the integration of heating systems, wick materials, nanofluids, external mirrors, external condensers, and phase change materials with nanoparticles significantly improving performance. Various studies have showcased the benefits of modified designs, such as pyramidal absorbers, convex and dish absorbers, and conical absorbers, in increasing evaporation surface area and freshwater output. Response surface methodology is effective for optimizing solar still performance with different nanoparticles. Global freshwater shortage problems could be addressed by this technology.

5.5 Tubular Solar Stills

When comparing the other stilled solar collectors to the tubular still solar collectors, using some modifications and nanoparticles, the tubular solar stills (TSS) are quite efficient [98]. Nonetheless, TSS systems are more complicated and expensive to manufacture.Kabeel *et al.* (2020) reviewed tubular solar stills, discussing the designs, performance, as well as the economic analysis, of the designs [99]. The review examines experimental and theoretical studies of both horizontal and vertical types of TSS. It drew attention to the elements that affect their output and the various approaches used for their productivity improvement. The study also included an economic appraisal on TSS that explained the cost per kilo of produced water, the payback period, and costs overall. Malaeb *et al.* (2014) looked at the influence of cover geometry on the performance of a modified solar still [100], to which they added a gently rotating drum. Adding the rotating cylinder allows for the water to form a thin layer, which increases the amount of evaporating water. Cover geometry was investigated with three orientations of coverings: double-sloped, single-sloped, and curved. A control double sloped still was also built for comparison. The experimental results revealed that the modified stills performed better, with overall productivity improvements of between 200% or 300%. The authors examined the correlation between temperature change and productivity and noted that both the temperature of the water and of the system, were important for the stills productivity. The study examines the exergy, performance, environmental, and economic factors of solar stills [101]. The active solar still was more efficient than the passive one in energy use and annual return. Economic analysis revealed that the passive still made distilled water at a lower cost, with a payback period of about 7.7 years. In contrast, the active still had a higher production rate and required less space, making it a viable and effective choice.The study looked at how different materials, including black fiber, black dye, and dried black Luffa acutangula fibers, affect the performance of cylinder sector solar stills (CSSS). This was compared to double-slope solar stills [102]. Researchers have explored various modifications and designs for solar stills, like fins, adjustable cover shapes, and energy storage materials, to improve their output and efficiency. The results of the investigation indicate that the best configuration is the CSSS with black dye and black natural fiber. It has the shortest payback period and the lowest CPL. According to the study, phase transition materials, nanoparticles, and external reflectors might be added in the future to enhance solar still performance. Compared to the

double slope and pyramid solar stills with the raised basin, the tubular solar still performs better with Ag nanoparticles [103]. Heat transfer characteristics are enhanced by a covering of nanoparticles. The effectiveness of a newly designed drum solar still equipped with reflectors was examined under combination conditions. The design supported a constant head tank to maintain water depth and included rotating drum and reflectors were common among the designs [104]. The modified drum SS certainly has its benefits due to the innovative design and the effectiveness of reflectors and nanoparticles. These features substantially increase the water productivity and decrease the cost of desalinated water.Abdullah *et al.* (2024) reviewed and reported published works considering the different combinations of these techniques and materials in the design and construction of tubular solar stills [105]. Which includes the techniques and materials discussed were geometry, heat-absorbing materials, condensation surfaces, and new additions with nanofluids, PCMs, and thermal storage material. They also explored alternatives to increase efficiency, including spinning cylinders, glass cooling, water preheating, and different designs of absorbers. The authors recommended that future investigations on tubular solar distillers should involve tests on spinning tubular distillers under different conditions as well as, the electric fogging using a photovoltaic-powered system in combination with thermoelectric generators and PCMs.

5.5.1 Preheating the Feed Water

Preheating saline water regularly always has a beneficial effect on productivity. For instance, SS needs warm water to promote evaporation and yield, while ETC has the ability to maintain the water at a higher temperature [106]. An alternative method of preheating the water using a renewable energy source is an electrical heater powered by a photovoltaic (PV) panel [107].

5.5.2 Absorber with Wick Material

The wick and wick materials are significant as a higher wick improves performance while reducing the cost [108], wick cords heat water present in the base [109]. Furthermore, these cords keep the wick surface wet by removing saltwater with ease. The design of the wick cords guards against energy waste, while also preventing any wasted water. The angle of the tube may also play a role in performance.

5.5.3 Combination of Several Techniques

The revolving drum, which is located in the basin, significantly contributes to the evaporation process or the drum distiller [110]. The drum solar still, which consists of a solar water heater, an external condenser, and running nanoparticles at 0.1 rpm as the configuration achieves the highest efficiency. A new design is the convex tubular solar still (CVTSS), which utilizes a convex absorber as opposed to a flat plate to increase vaporization and exposure to the surface area [111]. The CVTSS has better productivity and efficiency versus the traditional tubular solar still (TSS). Maximum results occurred when a jute fabric was combined with the nanocomposites. The CVTSS, with the suggested modifications, significantly improves productivity and efficiency compared to the traditional TSS. To address the low efficiency of conventional solar stills (CSS), a rotating cylinder, PCM, nanoparticle coating, and parabolic solar concentrator are used [112]. The solar concentrator can be employed to focus sunlight into the backside of the drum way increase the evaporation rate. However, this would significantly increase the glass temperature adversely affecting condensation [113]. The authors used two techniques to mitigate this effect, the first was to use PCM containing silver (Ag) to absorb energy in the high-radiation phase and then give energy back in the low-radiation phase when condensation occurs. The second method was to use a fan to condense any vapor on the outside. The modified solar still shows a shorter payback period compared to a conventional still. The use of the Ag nanoparticles in the PCM improved thermal conductivity and increased an overall thermal efficiency [114]. The corrugated drum solar still utilizes a corrugated drum surface, black paint reinforced with Ag nanoparticles, and a PCM with Ag nanoparticles.To conclude, tubular solar stills with nanoparticles have been shown to have good performance despite the requirements for manufacturing them being complex and expensive. There are numerous designs and modifications including rotating drums, changes to the cover geometries, and phase change materials combined with nanoparticles which have all shown enhancements in productivity and efficiency of solar stills. Preheating saline water has a positive effect on the performance of the solar stills while wicks, inclination, and rotating cylinders show strong improvement in performance. Novel designs such as the drum distiller and convex tubular solar still show promising results for enhanced evaporation and productivity. Economic analyses confirm that these designs yield better efficiency and productivity than conventional solar still designs.

6. Conclusion

Safe, accessible water is essential for drinking, household tasks, crop production, and other purposes as well. There are still significant disparities in providing access to safe water, adding to the health risk from waterborne diseases. The necessity for a practical, sustainable, and cost-effective solution is highlighted by the fact that conventional water treatment techniques can be extremely costly, ineffective, and energy intensive. Solar desalination employs solar energy to purify water. These systems are useful everywhere, but especially in areas that are isolated or in deserts where freshwater is a limited resource, even if they deliver a low yield. This review summarizes the importance of various factors: solar radiation, solar absorption, and the use of advanced materials and technologies, in underlining the prospects for multiplicity of changes and innovative to achieve productivity and efficiency improvements chosen for solar stills.A variety of solar still types have been studied in a systematic way, including but not limited to hemispherical, pyramid, tubular, single-slope, double-slope types, all of which have their merit. Additions such as preheating vessels, metal trays, wicks and fins, reflectors, external condensers and inverted collectors and phase change materials (PCMs) are likely to increase productivity. Single-slope solar stills are a simple design and have low production, while double slope designs have two surfaces that create vapor condensation. Shape and surface area of hemispherical and pyramidal type stills are the most efficient.Although tubular solar stills are complicated and expensive to manufacture, they are considered high performance, especially those utilizing nanoparticles and rotating drums. Economic reviews imply that although these designs may have a higher upfront cost, they may be more efficient and productive over time.In summary, renewable energy, especially solar desalination, has great potential for providing clean water. However, more research and development are needed to make these technologies affordable and available.

Author Statements:

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