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Recent Advances in Solar Still Technology: Design, Performance Enhancement, and Thermal Energy Storage.

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ABSTRACT

Solar stills offer a cheap means of generating potable water from saline or contaminated sources, employing solar energy as heat. Their simple construction, minimal maintenance, and suitability for decentralized use have drawn researchers' interest. Thus, despite low yields in conventional configurations, boosting solar still productivity remains a research focus. This review surveys recent progress in solar still technology, emphasizing how geometry relates to heat and mass transfer and to design optimization. Following a presentation of the fundamental physics of solar distillation, the article reviews the most common designs: single-slope, double-slope, pyramid, inclined, stepped, multi-basin, tubular, and hybrid stills. The principal ambient and operational factors governing evaporation and condensation in a solar still are then examined. Special emphasis is given to enhancement techniques, including passive and active approaches, thermal storage, phase change materials (PCMs), nano-PCM, nanomaterials, modified absorber surfaces, condenser cover cooling, and hybrid renewable systems. Beyond distillate yield, the article also assesses thermal and exergy efficiencies alongside economic and environmental gains from various solar still technologies. Key obstacles to productivity enhancement were pinpointed, such as inconsistencies in climate data, water depth, basin geometry, water measurement, and operation time. The study further identifies research gaps in solar still studies: long-term trials, procedural standardization, material durability evaluation, economic analysis, and optimization of combined geometries and advanced thermal storage. This work guides the selection of suitable configurations and enhancement techniques for specific decentralized freshwater production applications.

1. Introduction

Water is essential for human life and socioeconomic development. Only about 71% of the Earth's surface is covered by water, and only about 2.5% of that is fresh water available for human consumption. Access to clean water has become a growing concern for many countries as water becomes scarcer. The causes of this include: increasing population, industrialization, agricultural needs and the lack of freshwater resources themselves. This poses a serious threat to human life and well-being. Figure 1 below shows the number of people who die due to unsafe water sources per year [1].

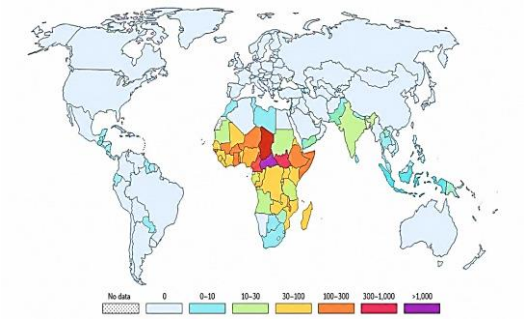


Fig. 1 Estimated annual number of deaths due to unsafe water[1].

Desalination is an effective way to obtain brackish or saline water. Conventional desalination technology requires extensive use of energy and infrastructure, which is not always accessible in remote, resource-limited areas. Solar power can be used to generate freshwater by supplying at least a part of the thermal energy needed to desalt water. Solar desalination is a process in which water is evaporated and condensed, leaving behind most of the salts and other nonvolatile contaminants in solution.

The solar still, which is characterized by a simple design, low energy consumption and ease of maintenance, is one of the solar desalination technologies most promising for decentralized freshwater production. Research at an early stage established the basic heat- and mass-transfer mechanisms of the solar still process, clarified the relationship between various environmental and design parameters and fresh water production [2], [3]. Later review studies focused on summarizing the development of various solar still designs and the main methods for improving productivity [4]. However, most solar stills have proved to give low yields of fresh water, limiting their widespread use. The optimization of solar energy collection and evaporation processes as well as condensation is therefore the main goals for solar still improvement studies.

The amount of freshwater yield from a solar still depends on several factors. The most common and significant parameters are solar radiation, air temperature, wind speed, water depth, cover tilt and material, the basin temperature, the temperature of the condensing cover glass. The temperature difference between the evaporating and condensing surfaces. Solar radiation, air temperature, and wind speed are controlled by the external environment, while variables such as water depth, tilt. Cover materials can be changed during solar still operation [5].

1.1 Solar energy

Solar energy is a clean and renewable energy source, which can be used to produce freshwater from saline or contaminated water. One of the simplest applications is solar distillation which is achieved by transferring the solar energy to the water, causing evaporation, and then condensing the water vapor on a cooler surface which yields fresh water. As part of this process, most dissolved salts and many contaminants are left behind in the original water, thus improving the quality of water collected. Solar stills are useful in small scale applications and remote locations as they are low energy consuming and have a simple structure [6]. Solar energy can also be combined with photovoltaic systems to supply the electricity required for membrane-based desalination processes such as reverse osmosis. Therefore, solar-based purification systems provide an attractive alternative for regions suffering from freshwater scarcity, especially where solar radiation is available for long periods of the year[7][8].

2. Review of methodology

A literature search was conducted in order to identify recent investigations concerning solar still design, performance enhancement, thermal energy storage, and desalination performance. The search was carried out employing Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar. The principal keywords comprised “solar still,” “solar desalination,”

"solar distillation," "solar still performance," "performance enhancement," "phase change materials," "nanomaterials," "thermal energy storage," "energy efficiency," and "exergy efficiency." Various combinations of the specified keywords were employed to locate pertinent publications.

The review concentrates primarily on studies published between 2020 and 2026, while earlier studies were incorporated when they provide the essential models, governing equations, or performance indicators required for solar still analysis. Studies were incorporated into the review when they addressed solar still design, operating parameters, performance enhancement, thermal storage, productivity, energy efficiency, or exergy performance. Studies that were unrelated to solar desalination or that reported inadequate performance details were omitted from the analysis.

The included studies were categorized in accordance with the solar still configuration, enhancement technique, operating conditions, productivity, and performance indicators. Particular attention was devoted to comparing the performance of solar stills with that of the conventional design. Furthermore, the limitations inherent in the reviewed enhancement techniques were identified. The review additionally encompasses previous studies with comparable objectives so as to identify research trends and gaps [5], [6], [9].

3. Governing equations

The equations governing the main heat-transfer processes and distillate production in solar stills are presented here. They provide the basis for assessing the thermal performance and behaviors of various configurations and enhancement techniques [9], [10]. The mathematical treatment of solar stills is based on established heat- and mass-transfer relationships developed in early solar-distillation studies

3.1 Energy balance

The energy balance of the water in the solar still can be expressed as:

$$I(t)\,\alpha w Aw + Qb - w = Q_{rad,\,w\text{-}g} + Q_{conv,\,w\text{-}g} + Q_{evap,\,w\text{-}g} + m_w C_{p,w}\frac{dTw}{dt} \quad (1)$$

where $I(t)$ is the incident solar radiation, αw is the absorptivity of water, Aw is the water surface area, $Qb-w$ is the heat transferred from the basin to the water $Q_{rad,\,w\text{-}g}$, and, $Q_{conv,\,w\text{-}g}$, and $Q_{evap,\,w\text{-}g}$ represent radiative, convective, and evaporative heat transfer from the water to the glass cover, respectively.

3.2 Evaporative heat transfer

The evaporative heat transfer from the water surface to the glass cover is given by:

$$Q_{evap,w\text{-}g} = h_{evap}\,Aw\,(Tw - Tg) \quad (2)$$

The evaporative heat-transfer coefficient can be calculated as:

$$h_{evap} = 0.016273\,h_{conv}\,[(Pw - Pg)/(Tw - Tg)] \quad (3)$$

where h_{evap} is the evaporative heat-transfer coefficient, h_{conv} is the convective heat-transfer coefficient, Pw and Pg are the saturation vapor pressures at the water and glass-cover temperatures, respectively.

3.3 Distillate productivity

The instantaneous distillate production rate can be obtained from the evaporative heat transfer:

$$\dot{m}d = Q_{evap,w\text{-}g} / hfg \quad (4)$$

where $\dot{m}d$ is the distillate mass flow rate and hfg is the latent heat of vaporization.

3.4 Latent heat of vaporization

The latent heat of vaporization can be calculated as:

$$hfg = 2.4935 \times 10^{6}\,[1 - 9.4779 \times 10^{-4}\,Tw + 1.3132 \times 10^{-7}\,Tw^{2} - 4.7974 \times 10^{-9}\,Tw^{3}] \quad (5)$$

where hfg is expressed in J/kg and Tw is the water temperature in °C.

3.5 Daily productivity

The daily productivity of the solar still can be expressed as:

$$Pd = Md / Ab \quad (6)$$

where Md is the total daily distillate mass and Ab is the basin area.

3.6 Thermal efficiency

The daily thermal efficiency of the solar still can be expressed as:

$$\eta th = [\Sigma\,(Md\,hfg) / (3600\,Ab\,\Sigma I(t)0] \times 100 \quad (7)$$

where ηth is the thermal efficiency, Md is the distillate production,

Ab is the basin area, and I(t) is the solar radiation intensity.

3.7 Exergy efficiency

The exergy efficiency can be expressed as:

$$\eta ex = (Exout / Exin) \times 100 \quad (8)$$

The exergy associated with the produced distillate can be expressed as:

$$Exout = (Md\ hfg / 3600)\ [1 - (Ta + 273.15)/(Tw + 273.15)] \quad (9)$$

The exergy of the incident solar radiation is:

$$Exin = Ab\ I(t)\ [1 - 4/3\ (Ta/Tsun) + (1/3)\ (Ta/Tsun)^4] \quad (10)$$

where Ta is the ambient temperature in K and Tsun is the effective sun temperature, generally taken as approximately 6000 K.

4. Distillation solar stills

Solar distillation is a thermal desalination method which uses the heating energy of the sun to separate freshwater and saline or contaminated water by repeated evaporation and condensation. The idea is to replicate on a small-scale, the natural hydrological cycle where the sun's energy is used to evaporate water, and the condensed vapor is deposited on a generally cooler surface. Solar distillation is attractive, because it can utilize solar radiation as a main energy source, compared with the other desalination technologies, which typically need large amounts of electrical or thermal energy. In regions with limited access to electricity and water systems, solar distillation may be a more suitable technology than other conventional desalination methods [11][12].

A solar still is the simplest device used to accomplish this process. It is traditionally composed of a relatively shallow water basin, clear condensing cover, thermal insulation and a system to capture the resultant distillate. Most of the solar radiation goes through the clear cover and is absorbed by the water and the basin, which raises the water temperature and evaporation. The water vapor formed then flows towards the inside surface of the clear cover, where it cools down and forms water droplets. Most of the dissolved salts and non-volatile contaminants stay in the basin, while these droplets run down the inclined cover and are picked up as distilled water [13].

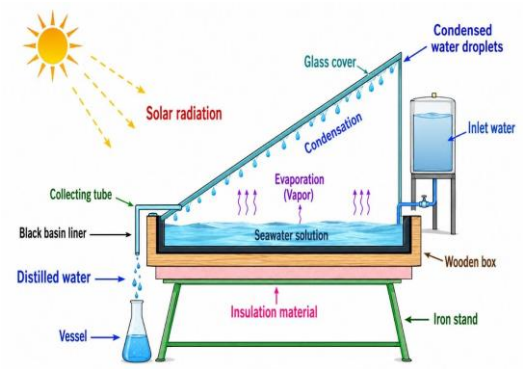


Fig.2 Solar water distillation process [14].

This means that the performance of a solar still is dependent on the interplay between solar energy absorption, evaporation, vapor transport and condensation. The increase in the temperature difference between the water in the basin and the condensing surface will generally increase the evaporating rate and will make the mass transfer driving force greater, while keeping the condensing surface relatively cool will make the condensing rate greater. Thus, the thermal characteristics of the basin, water volume and depth, optical properties of the basin cover, its angle and inclination, ambient conditions, and heat losses away from the still walls all affect the amount of freshwater generated. The studies that have been conducted in this field have therefore shown that productivity of distillate is influenced by the following main parameters: solar radiation, ambient temperature, water depth, water temperature in the still, wind and thermal characteristics of the still [15].

Despite its simple operating principle and low maintenance requirements, the conventional solar still is characterized by relatively low freshwater productivity because only a fraction of the incident solar energy is effectively utilized for evaporation. A considerable part of the absorbed energy can be lost through convection and radiation from the cover and through conduction across the walls and bottom of the basin. Moreover, the evaporation rate decreases when the temperature difference between the basin water and condensing cover becomes small. The restrictions outlined here have led to the study of various other geometries of the still, which seek to increase the evaporation or condensation surface area, increase the amount of solar radiation received by the condenser, reduce the condenser thermal losses, or recover some of the condenser latent heat released in the condensation process [16].

4.1 Solar still fabrication

The physical configuration of a conventional solar still typically comprises a sealed airtight basin lined with a dark absorber plate to holding raw water, covered by an inclined transparent glazing top [17]. During the fabrication process, structural design dictates the integration of back insulation to trap heat, alongside built-in collection troughs to channel the purified condensate toward storage [18]. The distillation mechanism is completely based on the greenhouse effect mechanism in which the solar radiation goes through the glass cover, the saline water evaporates, and then the saline water is continuously condensed on the cooler inner surface of the glass. [19], to achieve maximum thermal output, the assembly must adhere to specific geometric configurations, which are systematically defined in the following benchmark criteria:

Table 1

Standard geometric and thermal parameter for a conventional solar still [20], [4].

Design parameter	Target value	Technical justification
Glass Cover Tilt Angle	Φ to Φ + 10° (where Φ is the local latitude)	Maximizes solar irradiance capture and ensures seamless condensation flow without dripping back.
Basin Water Depth	1.0 cm - 3.0 cm	Low thermal capacity allows rapid heating and faster evaporation onset.
Insulation Thickness	2.5 cm - 5.0 cm	Minimizes conductive heat losses through the bottom and side walls of the basin.
Absorber Plate Coating	Absorptivity ≥ 0.90 (Matte Black)	Converts the maximum percentage of incident solar radiation into sensible heat.
Cover Material Thickness	3.0 mm - 4.0 mm (Tempered Glass)	Balances high solar transmissivity with structural durability against wind and thermal stress.
Insulation Conductivity (k)	≤ 0.04 W/m·K (e.g., Polyurethane/Rockwool)	Restricts thermal dissipation to the surrounding environment to sustain high inner temperatures.

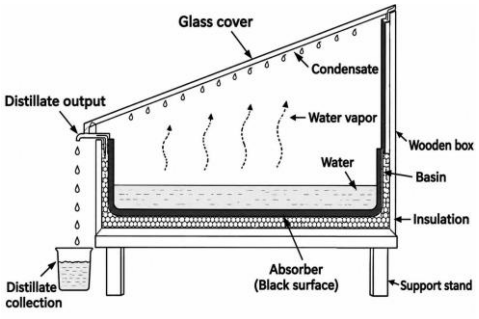


Fig.3 Schematic diagram of the conventional solar still.
Source: Author own illustration.

4.2 Types of solar still

Solar stills can be classified according to their operating mode and energy utilization into passive and active systems, while further distinctions include direct and indirect

distillation and single- and multi-effect arrangements. Hybrid systems represent another approach in which solar distillation is coupled with an additional technology or energy source. These classifications can overlap within the same system, whereas the geometrical forms of solar stills are discussed separately under solar still configurations [21].

4.2.1 Passive Solar Still

Passive solar stills rely on the natural availability of solar energy and require limited auxiliary equipment, which makes them relatively simple to construct and operate, particularly for small-scale and decentralized water production [22].

4.2.2 Active Solar Still

Active solar stills are designed to provide extra thermal or mechanical support in order to provide more energy to the evaporation process. It can be coupled with other external heat sources, such as solar collectors, concentrating systems, heat exchangers to enhance the production of freshwater [19].

4.2.3 Hybrid Solar Still

Hybrid solar stills are solar stills that are hybridized by other technology or energy source to overcome the limitations of solar availability. These can include thermal storage, photovoltaic/thermal components, thermoelectric components, or even other supporting heating/cooling technologies [23].

4.3 Solar Still Configurations

The geometric arrangement of a solar still affects the exposed evaporation area, solar-energy absorption, vapor transport, and condensation process. Consequently, different configurations have been developed to improve the utilization of available solar energy while maintaining practical construction and operation.

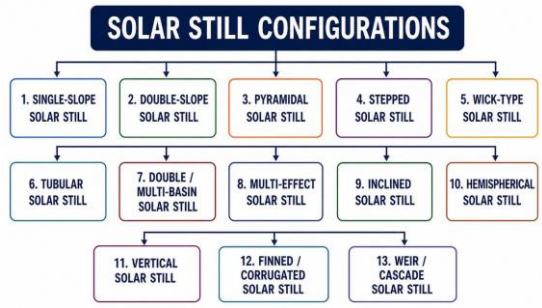


Fig. 4 Configurations of solar still.

Source: Author own illustration.

4.3.1 Single-Slope Solar Still

The single-slope design is based on a single inclined transparent surface over a single basin. One of the solar still configurations that is most widely researched is its simple structure and relatively short vapor path [24].

4.3.2 Double-Slope Solar Still

Double slope design is a system of two transparent covers mounted on the opposites slopes of the basin. This allows for two condenser surfaces and the daylight heat to come in from various angles throughout the day [25].

4.3.3 Pyramidal Solar Still

A pyramidal solar still employs several inclined transparent surfaces that converge toward an upper point. Its multidirectional geometry provides good solar exposure and a relatively large condensing surface [26].

4.3.4 Stepped Solar Still

Stepped solar stills comprise a sequence of shallow stages across which saline water is distributed, thereby enlarging the exposed evaporation area and diminishing the thermal resistance linked to greater water depths [27].

4.3.5 Wick-Type Solar Still

A wick-type system utilizes capillary forces to distribute saline water as a thin film over the evaporation surface. This results in the largest possible surface area of water being exposed to the heating medium, thereby enhancing the rate of evaporation [28].

4.3.6 Tubular solar still

The tubular configuration is characterized by surrounding the evaporation zone with a transparent cylindrical or curved cover. The large condensation surface area and the multi-directional exposure to solar radiation make this design appealing for modified solar desalination systems [29].

4.3.7 Double-basin and multi-basin solar still

Double or multi-basin stills have additional water basins and/or evaporation stages added to the original still. The additional stage allows for more efficient use of thermal energy by letting the heat from one evaporation/condensation cycle be used to heat the next [19].

4.3.8 multi-effect solar still

Multi-effect configurations use successive evaporation–condensation cycles in which a fraction of the latent heat released may be reused in the next stage, cascading the heat and

improving the use of the supplied thermal energy [30].

4.3.9 Solar still with an inclined configuration

Solar stills of the inclined type employ an angled evaporation surface on which water is able to form thin layers. An increase in heat and mass transfer rates may be achieved through a decrease in the thickness of the water depth and alterations to the direction of flow. This design of still may be integrated with alternative enhancement techniques [31].

4.3.10 Hemispherical solar still

Hemispherical solar stills use a curved transparent cover over the evaporation basin. The dome-shaped surface provides a large condensation surface area and enables solar radiation to reach the system over a broad range of incident angles [32].

4.3.11 Vertical solar still

Vertical solar still is a type of solar still that has the evaporation and condensation surfaces mounted in a basically vertical position. This geometry reduces the vapor transport distance and has recently been studied with the wick-assisted and multi-effect designs [21].

4.3.12 Finned and corrugated solar still

The finned and corrugated type variations provide for the enhancement of the effective heat-transfer and evaporation area of the absorber surface. These geometric alterations can be used to enhance the thermal spreading as well as the area of saline water contacting the absorber [33] [34].

4.3.13 Weir-type and cascade solar still

Weir-type and cascade systems distribute saline water successively over inclined or stepped surfaces. The resulting thin water films increase the exposed evaporation area and improve the interaction between the heated surface and the flowing water [35].

5. Factors affecting solar still performance

The performance of a solar still can be controlled by various climatic, operating and design parameters which will control the rate of heat transfer, evaporation and condensation within the unit. The impact of some of these variables like solar radiation and ambient conditions, are imposed by the environment while others are controllable through the design and operating strategy of the still. The effect of these factors is especially significant because a variation of one parameter can cause a change in the temperature difference between the water and the condensing surface and therefore in the evaporation rate and in the daily distillate output.

5.1 Solar radiation

Solar radiation is the main energy source for solar distillation; therefore, it is one of the most relevant factors that influence still productivity. Increased incident radiation leads to more energy being transferred into the basin and water, which raises their temperatures and evaporation rates. Radiation also possesses a daily variation, which leads to a comparable variation in the amount of distillate produced, with the maximum production occurring at the time of maximum solar input. Effective radiation that reaches the evaporation surface could be altered by cloudiness, weather conditions, and the orientation of the still [36].

5.2 Ambient temperature

The effects of ambient temperature on the thermal performance of a solar still are two-fold: by reducing the temperature difference with the surroundings, a lower environmental temperature will result in lower heat losses from the still, as well as cause a reduction in the temperature of the condensing cover. At the same time, the temperature of the ambient air influences the ability of the cover to reject heat and maintain a suitable temperature difference between the evaporating water and condensing surface. Consequently, ambient temperature should be considered together with solar radiation rather than as an isolated parameter when evaluating still productivity [37].

5.3 Wind speed

The heat transfer conditions around the transparent cover are mainly influenced by the wind velocity. The moderate airflow can improve the heat rejection rate from the cover surface, so that the temperature of the cover surface can be lowered and the temperature difference between the water and the cover surface can be raised. This can promote condensation and thereby enhance freshwater generation. The effect is not always linear as the amount of air flow can be such that the convective heat losses from the still to the

surroundings can also increase, depending on the configuration and level of insulation [38].

5.4 Relative humidity and cloud cover

Moisture in the air may affect the condensation over the outside of the still. High RH decreases the drying capability of the air around the skin and could decrease the evaporating power of the outer cover. The effect of cloud cover is also taken into account as it decreases the amount of solar radiation reaching the absorber, which decreases the temperature of the water and the energy available to evaporate the water. These conditions are therefore of particular significance in comparing experimental results from different days [20].

5.5 Basin water depth

Depth of basin is one of the significant operating parameters which can be controlled in a conventional solar still. Typically, a shallow water layer will need less energy to heat it to an elevated temperature and thus there will be a rapid response to solar heating. An increase of the water depth requires a greater thermal mass to be heated, which may cause a slower increase in temperature and lower evaporation rates, particularly during initial evaporation.

Experimental and theoretical investigations have shown that the influence of water depth can be substantial, although its optimum value depends on the still geometry and other operating conditions [39].

5.6 Glass Cover Inclination

The angle of the transparent cover will influence the amount of solar energy that will enter the still, and will also influence the flow of condensed water to the collection channel. The internal vapor space and heat and mass transport between water surface and cover also are affected by an appropriate inclination. So, the best angle is not a universal one and is dependent on the geographical latitude, season, still geometry and the distance between the water surface and the cover. The choice of an unsuitable angle may affect the ability to absorb solar energy or affect condensation conditions and hence the overall yield [40].

5.7 Water–glass temperature difference

The difference in temperature between the evaporating water and the inner surface of the glass is one of the main forces which promotes evaporation and condensation within the still. A higher water temperature and relatively cooler condensing surface enhances the vapor-pressure difference and mass transfer to the glass. Therefore, it is necessary to keep this temperature difference to achieve a high evaporation rate. This temperature relationship can be altered by improvements in insulation, cover cooling, water heating or thermal-energy storage, which can impact productivity in part [19].

5.8 Basin and evaporation area

The effective evaporation area determines the amount of water exposed to solar heating and the available water–air interface for vapor generation. Increasing the absorber or evaporation area can provide a larger region for heat absorption and evaporation, particularly when the water layer remains shallow. This is the case though, and simply enlarging the area does not guarantee proportional improvement: the heat distribution, the vapor movement and the condensation capacity will have to be made compatible with the larger evaporation surface [41].

5.9 Feed-water temperature and flow conditions

The time taken for the water in the basin to reach the temperature suitable for evaporation will affect because of the initial temperature of the feed water. Water can be preheated before entering the water treatment system, which reduces the heat load that the sun has to supply during the operating period and thus increases the distillate production. In continuous or controlled feeding systems, the flow rate is also important because too much cold water added reduces the temperature of the basin, while a suitable flow rate keeps the temperature of the basin in an optimum range [42].

5.10 Salinity and water quality

The salt content affects the evaporation rate of the basin solution as increasing the salinity decreases the vapor pressure of the solution. As evaporation proceeds, salt concentration can progressively increase when the rejected brine is not replaced or diluted. This can cause an increase in the non-evaporation rate and can also result in salt build-up on the surface of the absorber, which will affect the heat transfer and require regular cleaning. Therefore, experimental results should be interpreted in relation to the initial water quality and any changes in water composition that occur during operation [43].

5.11 Insulation and thermal losses

Thermal insulation must be provided to prevent undesired heat transfer between the basin and the surroundings and between the absorber and the surroundings. To minimize heat loss from the bottom and side walls, there should be sufficient amounts of insulation so that a large percentage of the warming energy from the sun can be used for evaporating water and heating the water.

Better insulation thus results in improved energy conservation in the distillation unit and will raise the proportion of the absorbed energy used for freshwater production. The effectiveness of insulation depends not only on thickness but also on its thermal conductivity, installation quality, and continuity[44].

5.12 Glass thickness and optical properties

The clear cover serves two purposes: it allows solar radiation to pass through to the still and it serves as the main condensation surface. Thickness and optical properties thus influence the radiation received in the basin and thermal properties of cover. The thickness of the cover could be associated with the heat transfer resistance and thermal mass, while the transmittance depends on the amount of solar energy that enters the system. The optical and thermal properties of the glazing material should then be taken into account when selecting the material, not only thickness [45].

5.13 Condensation Gap

The condensation gap is the distance between the water surface and the inner surface of the glass cover. This parameter affects the vapor flow in the condensation zone and, as a result, the heat and mass transfer in the still. A large gap prolongs the vapor path and reduces the rate of vapor transportation to the condensation area, while a small gap can impede the vapor flow and prevent the condensate from properly draining. Thus, the gap should be set depending on the solar still geometry to ensure the vapor flow, its condensation on the glass cover, and the collection of the produced freshwater [46].

5.14 Orientation and Tracking

The direction of solar still determines the direction towards which the solar radiation reaches the absorber and transparent cover. An appropriate orientation can maximize the exposure to solar radiation in the operating period while an unfavorable position can minimize solar received radiation due to geometric shading and varying solar angles. Another possibility for more efficient utilization of the radiation is solar tracking, but the extra mechanical complexity and energy demands should be taken into consideration [47].

5.15 Surface cleanliness and dust deposition

The dirt on the clear cover causes a decrease in the transmittance of the cover, which in turn lowers the quantity of sunlight reaching the evaporation chamber. Also, deposited particles alter the thermal property of the cover and lessen the effectiveness of condensation. This is especially important in dry or dusty conditions, such as in the case of a solar still, where its efficiency could drop during the time between cleanings. Periodic maintenance of the facility's glazing surface is therefore crucial in order to preserve the optical stability of the surface [48].

5.16 Interaction Among Operating and Design Parameters

The effect of individual parameters cannot always be considered independently because solar-still performance results from the coupled interaction of thermal and mass-transfer processes. For example, the benefit of reducing water depth depends on the available solar radiation, while the effect of cover inclination is related to both the geographical location and the vapor-space geometry. Similarly, improved insulation may raise the basin temperature but can also influence the temperature of the condensing surface. Therefore, performance evaluation should consider the interaction among climatic, operating, and design parameters rather than attributing productivity changes to a single variable alone [49].

6. Performance enhancement techniques for solar stills

Traditional solar stills are noted for their straightforward construction and minimal reliance on external energy sources; nevertheless, their output tends to be constrained by incident solar radiation, thermal losses. The comparatively sluggish processes of evaporation and condensation. To address these constraints, a range of enhancement approaches has been devised to augment heat transfer, evaporation, condensation, and freshwater yield in solar stills.

6.1 Phase change materials (PCM)

Phase change materials store a considerable amount of thermal energy as latent heat during

periods of solar availability and release it gradually when the solar intensity decreases. Their integration with solar stills can therefore extend the evaporation period beyond peak sunshine hours and maintain freshwater production after sunset [50].

6.2 Nano-enhanced phase change materials (NPCM)

The relatively low thermal conductivity of conventional PCM can limit its charging and discharging rates. Dispersing nanoparticles within the PCM can improve its effective thermal conductivity and heat-transfer characteristics, making NPCM a promising approach for accelerating thermal storage and release in solar still applications [51].

6.3 Nanofluids and nanoparticle additives

Nanoparticles can be introduced directly into the basin water or used as part of a heat-transfer medium to modify its thermophysical and optical properties. Their application can enhance solar-energy absorption and heat transfer, thereby increasing the temperature of the evaporating water and improving distillate production [52].

6.4 Corrugated and modified absorber surfaces

Since the evaporation and heat transfer area is increased by corrugation and other surface modifications without much increase in the overall footprint of the still, the area is referred to as the "effective" area. Geometrical changes can improve the heat distribution and improve the evaporation of water compared to the flat absorber surface such as this [53].

6.5 Reflective surfaces

Additional solar radiation is directed towards the absorber by the use of internal and external reflectors, which boosts the amount of energy available for water heating and evaporation. The effectiveness of these depends on the position and orientation of the reflector, on its optical properties, and on the function of the still to absorb the extra radiation [43].

6.6 External heating

External heaters supply additional thermal energy to the basin water when solar radiation is insufficient. This approach can stabilize the evaporation process during periods of weak solar input, although the source of auxiliary energy must be considered when assessing the overall sustainability of the system [54].

6.7 Electrical heating

The temperature of the basin water can be raised directly by electrical heaters and evaporation can take place during periods of low radiation. Their integration is helpful especially for hybrid systems, but the demand for electrical energy can diminish the benefits of this technique if the electricity is made from conventional sources. [55].

6.8 Water circulation using pumps

Pumping-induced water circulation can enhance both the distribution of heat across the solar still and the thickness of the water layer on the evaporation surface. Nevertheless, the flow rate must be regulated appropriately, as elevated values may lead to a decline in productivity. As reported by Baharvand et al., raising the flow rate from 3 to 6 L m^{-2} day^{-1} can increase productivity by 3.5% during winter, while a further rise to 9 L m^{-2} day^{-1} may cause a reduction of roughly 14%. In winter and summer, the optimal flow rates are 6 and 10 L m^{-2} day^{-1}, respectively [46].

6.9 Solar collector–solar still integration

Coupling a solar still with a solar thermal collector provides preheated water or additional thermal energy to the evaporation chamber. This arrangement can extend the operating period and increase productivity, although the additional collector area and thermal losses must be considered in the overall system evaluation [56].

6.10 Photovoltaic/Thermal (PV/T) integration

PV/T systems can simultaneously produce electricity and thermal energy, allowing the electrical output to operate auxiliary components while the recovered thermal energy contributes to water heating. Recent hybrid configurations have demonstrated the potential of combining photovoltaic electricity, thermal recovery, PCM, and solar stills within a single desalination system [57].

7. Previous experimental work and analysis

In recent years, interest has been growing on how to increase the productivity by making modifications to improve evaporation, heat transfer, vapor movement or condensation. Instead of using a single enhancement method, recent studies have focused on various combinations of passive and active methods depending on the desired operating conditions

and the still configuration, where choice of modification is strongly dependent on the still configuration.

Sivasankar et al. (2023) [58] investigated a single-basin solar still equipped with a composite vertical wick consisting of polyester and cotton wrapped around a vertical wooden support. The composite wick increased the evaporation surface area and reduced the amount if bulk water requiring heating. The production of distillate was noticeably increased due to the use of the composite configuration compared to conventional and single material wick configurations, indicating the need to consider wick structure and material selection for improving passive evaporation.

Al-Dulaimi and Amori (2023) [59] experimentally examined a tracked tubular solar still coupled with a parabolic trough concentrator and a heat pipe. The heat pipe enhanced the dissipation of the thermal energy absorbed towards the saline water and the solar tracking ensured better exposure to the available radiation. They concluded that the heat-pipe configuration was effective in enhancing the productivity of freshwater as well as the thermal efficiency, which suggests that it can be especially effective for tubular stills when a high concentrated solar input is complemented with efficient heat transport inside the still.

Abdullah et al. (2023) [60] investigated a rotating-wick solar still with different porous belt configurations and quantum-dot nanofluid. The evaporating surface was continuously renewed with the help of the rotating wick and the thermal absorption was enhanced by using the nanofluid which also improved the water distribution. The study exemplifies how a mechanically renewed wetted surface can be combined with the use of advanced working fluids to overcome the limitations which are associated with the stagnant wetted surface.

Issaq et al. (2023) [61] experimentally examined a number of modifications to solar-still operation, including sensible heat-storage material and surface treatment. Their work highlighted that relatively simple materials can contribute to the productivity improvement without complex mechanical systems. The results also suggest that the effectiveness of such a modification depends on the way of the interaction of the added material with the basin water and the condensation surface and not only on the thermal properties of the material.

Dumka et al. (2024) [62] investigated a modified solar still with Plexiglas and jute fabric in order to promote to localize the heat and thin-film evaporation. The result was an increase in the distillate production with a decrease in the cost of produced water with the help of the modified configuration. The study is also important for passive enhancement as it exemplifies how, with increased distribution and thickness of the evaporating water layer, no external heating or pumps are required to be effective.

Baiee et al. (2024) [63] examined a pyramidal solar still with a rotational technique to improve its performance. The modification was intended to alter the thermal and mass-transfer conditions within the still and to increase the effectiveness of solar energy utilization. Such a configuration exemplifies the potential of controlled movement as an alternative to conventional static operation, particularly when the geometry of the still already provides multiple condensing surfaces.

Kerfah et al. (2024) [64] studied a basin solar still with an integrated condensation chamber and compared different cooling approaches, including thermoelectric and water cooling. Their results showed that the condensation side cooling has a significant effect on vapor condensation and productivity. The study also revealed that the effect of the various cooling arrangements on the basin was varied from that on the condenser and that it is necessary to optimize the overall evaporation–condensation operation and not just the operation of the condenser to increase the basin temperature.

Mandev et al. (2024) [65] investigated cellulose-based water-absorbing materials in combination with a Peltier condensation unit. Hemp and highly absorbing paper were examined as water distribution materials, while thermoelectrical cooling was used to enhance condensation. The study exemplifies the potential of combining passive evaporation enhancement with localized active cooling, providing a useful example of a hybrid approach in which evaporation and condensation are simultaneously addressed.

Yuvaraj et al. (2024) [66] investigated a solar still integrated with photovoltaic cells, focusing on the effective condenser-glass area. The effect of the electrical-generation component and condensation surface available was taken into account, revealing that geometry properties of the condensing region are still significant even with the use of photovoltaic technology. This

work is an argument for designing hybrid solar systems with regard to energy production and water production requirements, not separately.

Hyal et al. (2024) [67] combined a floating wick evaporation surface with an external condenser in a single-slope solar still. The arrangement separated part of the condensation process from the main still chamber and increased the available evaporation area through the wick. The numerical and experimental investigation demonstrates the potential of combining internal evaporation enhancement with external condensation, although the additional condenser increases system dimensions.

Daif et al. (2024) [68] investigated a concentrated solar still equipped with a sun-tracking mechanism. This tracking system was employed to keep the orientation of the solar source more favorable during the entire operating period whereas the concentration of the input of the thermal source into the still increased the heat input. The study shows that the benefit of active solar positioning in maximizing the useful fraction of the incident energy is offset by the mechanical and energetic complexity of the process and may be limited to practical use given the potential for significant increases in complexity and energy use.

Sharshir et al. (2024) [69] investigated a solar still coupled with large-capacity heating and cooling units and evaluated its thermal, environmental, and economic behavior. The study demonstrated that controlling the heating and cooling processes can considerably improve freshwater production compared with a conventional still. Nevertheless, the increased auxiliary equipment makes such systems more appropriate for applications where higher productivity justifies additional energy and capital requirements.

Singh et al. (2025) [70] examined the use of an Al_2O_3–CuO hybrid nanofluid in a solar still while varying the basin water depth. The combination of two oxide nanoparticles was intended to improve the thermal behavior of the working fluid, while water-depth variation allowed the interaction between thermal capacity and evaporation rate to be assessed. The study demonstrates that nanofluid enhancement cannot be evaluated independently of operating conditions, since excessive water depth can offset part of the thermal advantage obtained from improved heat absorption.

Sachidananda et al. (2025) [71] experimentally investigated a pyramidal solar still equipped with a low-power rotating fan and an ultrasonic humidifier. The fan enhanced vapor circulation through forced convection, whereas the ultrasonic humidifier increased vapor generation by producing fine water droplets. Although the ultrasonics system produced the highest distillate production from the tested systems, the strong reliance on electrical power is an important consideration in off-grid solar desalination; the high dependency on electrical power is a major factor for the ultrasonics system.

Saeed et al. (2025) [72] investigated a single-slope solar still incorporating a semi-elliptical absorbing base. The geometric modification was intended to alter the distribution of saline water and increase the effective heat-transfer area. This approach illustrates how absorber geometry itself can be used as a passive enhancement method, avoiding the additional energy consumption associated with active devices.

Khanjani et al. (2025) [73] studied a conventional solar still coupled with a cylindrical solar water heater and a Cu/Al_2O_3 hybrid nanofluid. The solar water heater provided additional thermal energy to the desalination unit, while the hybrid nanofluid enhanced the heat-transfer characteristics of the circulating fluid. The study represents a hybrid thermal approach in which external solar collection and nanofluid-based heat transfer are used together to increase freshwater production.

Jodha et al. (2025) [74] investigated a spherical solar still incorporating an axial absorber, wick layers, single-axis tracking, and a rear reflector. These changes were then introduced one by one which further increased the effective absorption of solar radiation and improved evaporation, thus bringing about a significant improvement in productivity as compared to the conventional configuration. The tracking and reflective portion create a much more complex system than most passive tracking systems, though.

Murad et al. (2025) [75] investigated a double-slope solar still incorporating rotating cylinders and PV-powered electric heaters. The rotating cylinders increased the effective evaporative surface and reduced the water-film thickness, while the PV-powered heaters supplied additional thermal energy. The combined configuration produced a considerable increase in freshwater productivity, demonstrating the potential of integrating mechanical evaporation enhancement with renewable-powered heating.

Ali et al. (2025) [76] investigated an integrated solar water treatment system that combined solar desalination with filtration and ultraviolet treatment. The experimental assessment demonstrated the potential of integrating complementary treatment techniques with solar distillation to improve the quality and suitability of the produced water for domestic applications.
Majeed et al. (2026) [77] investigated a single-slope solar still enhanced with porous absorbing materials, including melamine sponge and pumice stone. The porous structures had the effect of providing greater effective wetted area as well as encouraging the development of a thin layer of water on the surface of the absorber, thus aiding evaporation. This is attractive as it utilizes relatively simple materials and does not need continuous external power, but the long-term stability and salt accumulation characteristics of porous absorbers, need to be considered.
Devan et al. (2026) [78] examined a double-slope solar still by varying the glazing arrangement and spacing between the condensing surfaces. They have showed that solar-still performance of solar still is not only related to the absorber and water-side property but also the optical and thermal property of the glazing system. Geometric design is an important enhancement parameter since it can affect vapor transport and condensation between surfaces when optimized.
Elsayed et al. (2026) [79] integrated a medium-temperature phase-change material into a single-slope solar still to provide thermal buffering and extend the effective evaporation period. The PCM-aided system generated significantly higher freshwater yields than the traditional still, with an extra hybrid set-up that incorporated hot domestic water as an extra heating source. The study adds to the understanding of the importance of the role played by latent heat storage in minimizing the mismatch between demand for evaporation and the availability of solar energy for the day.
El-Fakharany et al. (2026) [80] investigated a tubular solar still using porous-media coating together with carbon quantum dots and graphite nanoparticles. The porous coating increased the effective evaporation surface, while the advanced carbon-based nanoparticles were introduced to improve thermal absorption and heat transfer. This combination represents a recent trend toward multifunctional nanomaterial-based enhancement, although the additional material cost and long-term stability of such systems remain important issues for large-scale implementation.
Another recent study investigated a solar still using sand-filled soda cans as sensible heat-storage elements and combined the experimental work with artificial neural network prediction. The storage units were designed to retain thermal energy during periods of high solar input and release part of this energy during declining radiation. The integration of experimental thermal storage with machine-learning prediction reflects the increasing emphasis on improving both the physical performance and operational optimization of solar desalination systems [81].

Table 2
Comparison between previous studies in solar stills

Study	Still / technique	Result	Research Gap
1. Sivasankar et al. (2023) [58]	vertical wick	35.35%	Long-term durability of the vertical wick requires further investigation.
2. Al-Dulaimi & Amori (2023) [59]	heat pipe	25–40%	Practical complexity of the heat-pipe configuration requires further evaluation.
3. Abdullah et al. (2023) [42]	preheating and PCM	115%	The individual contribution of preheating and PCM requires further assessment.
4. Abullah et al. (2023) [60]	Rotating wick with QD	improved	Complexity of the rotating wick with quantum dots requires further investigation.
5. Issaq et al. (2023) [61]	Modified still	Improved	Further validation of the modified still under different conditions is required.

6. Dumka et al. (2024) [62]	Plexiglas and jute	improved	Long-term durability of the Plexiglas and jute materials requires evaluation.
7. Baiee et al. (2024) [63]	Rotating pyramid	improved	Maintenance requirements of the rotating pyramid require further investigation.
8. Kerfah et al. (2024) [64]	TEC with cooling	Improved	Additional energy demand of thermoelectric cooling requires assessment.
9. Mandev et al. (2024) [65]	Cellulose with Peltier	Improved	Electrical power input of the Peltier-based system requires further evaluation.
10. Yuvaraj et al. (2024) [66]	PV with condenser	Improved	Economic cost of integrating PV and a condenser requires assessment.
11. Hyal et al. (2024) [67]	Wick and condenser	Improved	Additional complexity of the wick and condenser configuration requires investigation.
12. Daif et al. (2024) [68]	Solar tracking	Improved	Economic implications of solar tracking require further evaluation.
13. Sharshir et al. (2024) [69]	Heating and cooling	Improved	Additional energy demand of heating and cooling requires assessment.
14. Singh et al. (2026) [70]	Al_2O_3–CuO nanofluid	Improved	Applicability of the Al_2O_3–CuO nanofluid requires further investigation.
15. Sachidananda et al. (2025) [71]	Fan with ultra-sonic	Improved	Additional power input of the fan and ultrasonic system requires evaluation.
16. Saeed et al. (2025) [72]	Semi-elliptical base	Improved	Further validation of the semi-elliptical base under different conditions is required.
17. Khanjani et al. (2025) [73]	Heater with hybrid NF	Improved	Practical complexity of the heater and hybrid nanofluid requires investigation.
18. Jodha et al. (2025) [74]	Spherical and multiple	Improved	Contribution of the spherical and multiple configurations requires further assessment.
19. Murad et al. (2025) [75]	Double-slope with hybrid	Improved	Further optimization of the double-slope hybrid configuration is required.
20. Majeed et al. (2026) [77]	Porous absorber	Improved	Long-term durability of the porous absorber requires further investigation.
21. Devan et al. (2026) [78]	Slope and spacing	Improved	Integration of slope and spacing parameters requires further assessment.
22. Elsayed et al. (2026) [79]	PCM	Improved	PCM thermal conductivity and its effect on performance require investigation.
23. El-Fakharany et al. (2026) [80]	Porous-nanoparticles	Improved	Long-term stability of the porous-nanoparticle enhancement requires evaluation.
24. Kumar et al. (2026) [81]	Sand storage with ANN	Improved	Further optimization of sand thermal storage is required.

In the recent development of solar stills, the productivity has been shown to be enhanced by the use of wick structures, porous absorbers, nanomaterials, thermal storage, active cooling and modified geometries. Most investigations, though, have focused on one enhancement

strategy, or on incorporating multiple strategies without making clear what type of contribution each strategy makes. In particular, while PCM components can increase the time the stored thermal energy can be used, the thermal conductivity of the stored thermal energy may be lower, which can limit the flow of the stored thermal energy to the basin water. The use of nanoparticles with PCM is one of the potential solutions to enhance its thermal transport property, however, the efficiency of the nano-enhanced PCM is greatly dependent on the amount of nanoparticles in the PCM, their dispersion and the way the storage material is loaded into the still.

Another drawback is the lack of integration of thermal storage with the enhancement of the evaporation surface and still geometry. There are many reported systems that increase evaporation, many that increase condensation, and few that have systematically looked at the interaction among these processes. Furthermore, some high-performance setups involve the use of fans, pumps, tracking mechanisms, thermoelectric systems, or external heating systems, which can contribute to higher energy usage, expenses, and complexity. Thus, a relatively simple passive configuration which enhances heat transfer and evaporation but still conserves heat for periods of low solar radiation would still be desirable. A comprehensive performance evaluation of the nano-enhanced PCM still under various still configurations and operating conditions is also required to determine the appropriate concentrations and configurations of the material without sacrificing the ease of use of the system. This gap offers scope for further experimental exploration of novel thermal-storage/heat-transfer enhancement approaches for solar desalination.

8. Critical synthesis

The reviewed studies demonstrated that the performance of solar stills is closely related to both the enhancement technique and the operating conditions. The passive modifications, including wicks, fins, porous absorbers, reflectors and stepped configurations, generally enhance the evaporation and heat transfer processes without continuous external power [58]-[63]. However, the reported improvements depend on the water depth, solar radiation, basin geometry, and the reference still, making the comparisons between studies challenging. For instance, the utilization of rotating and modified geometries can increase not only the effective evaporation area, but also the maintenance and design complexity [63], [74].

The thermal storage and hybrid systems offer an alternative by maintaining continuous evaporation after the period of the maximum solar radiation. The PCM-based systems and sensible heat-storage materials can prolong the useful operation period, while the nano-enhanced materials are designed to enhance the heat transfer [79]-[81]. However, their effectiveness can be affected by the thermal properties, charging conditions, material configurations, and long-term stabilities. Similarly, the studies with porous absorbers and nanomaterials reported enhanced evaporation, but the material longevity and the impact of nanoparticle incorporation demand further evaluations

The active and hybrid enhancements, including thermoelectric cooling, Peltier, fans, ultrasonic devices, solar tracking systems. Auxiliary heating, can provide additional heat and/or mass transfer mechanisms to further increase freshwater productivity [59]– [70]. However, the additional energy input or complexity must be carefully considered when assessing their overall performance. Indeed, the reported higher productivities do not always represent the enhanced practical performance if the energy consumption or complexity level is not considered.

The differences in reported performance cannot be simply explained by the enhancement technique because the changes in climate, solar radiation, water depth, still geometry, operating period, reference configuration. Measurement conditions can significantly vary the results. In addition, many reviewed studies utilized a combination of different enhancement techniques[70], [77], [80] , making it difficult to distinguish their individual contribution [66]-[75]. Future studies should focus on comparative experiments under similar operating conditions and report the freshwater productivity in combination with net energy consumption, exergy performance, economic costs. Long-term durability. Indeed, such standardized assessments will support the identification of the practical effectiveness of different solar still enhancement techniques.

Economic factors can also be significant in assessing the practicality of the suggested solar still improvement methods. Daif et al. and

Sharshir et al. included economic analysis in the evaluation of the solar tracker concept and auxiliary heating and cooling system, respectively. Another group that considered economic factors in their study was Majeed et al., who analyzed the impact of economic indicators alongside thermal factors and the effect of porous material on the environment. Additionally, El-Fakharany et al. mentioned that the additional cost of using porous coating with carbon-based nanoparticles can be regarded as an essential factor in the practical application of the enhanced solar still. Thus, it is necessary for researchers to analyze the amount of freshwater produced by the still alongside the initial, maintenance. Operation costs and energy consumed by the solar still under the same conditions.

9. Comparison of quantitative findings solar still

A concise quantitative comparison of selected recent studies is presented in Table 3. The reported values are retained under the original experimental conditions and are intended to illustrate the range of improvements achieved through different enhancement approaches.

Table 3.
Selected Quantitative Findings from Recent Solar Still Studies.

No.	Enhancement/Modification	Key result with units	improvement over baseline (%)	Ref.
1	Inclined perforated rectangular fins	Average yield: 3.9–5.7 L/day (Feb–Aug)	16–54%	[82]
2	Internal reflectors + fins	Average monthly productivity increase: 3.014 L m^{-2} day^{-1}	Improved performance	[83]
3	Internal reflectors	Productivity improvement varied with month	About 34%	[84]
4	Stepped basin + internal reflectors	Daily efficiency: 56% vs. 34% for conventional still	75%	[85]
5	Pin-finned wick	System efficiency: about 55%	More than 23%	[86]
6	Finned-wall / built-in condenser	Daily productivity increases up to 92.3%	Up to 92.3%	[87]
7	Lenses + external reflector	Maximum yield: about 2.5 kg m^{-2} day^{-1}	About 32%	[88]
8	Graphite / sensible heat storage	Productivity enhancement reported	75-80%	[89]
9	PCM-based pin-finned heat sink	Productivity enhancement reported	17%	[90]
10	Internal cooling coil	Productivity increase: 25%; efficiency increase: 4.3%	25%	[91]
11	Partially cooled condenser	Productivity enhancement	11.8%	[92]

		reported		
12	Evacuated tubes + condenser + fins	Combined thermal/exergy performance improved	73.5%	[93]
13	Wick-finned absorber + nano-enhanced PCM	Enhanced productivity reported	Enhanced yield	[94]
14	Corrugated absorber + nano-PCM	Thermal efficiency: 40.3% (inclined) and 50.9% (pyramidal)	139.2 % / 125.7 %	[95]
15	Black rubber / black gravel storage	Productivity increase: 19-20%	19% - 20%	[96]
16	External condenser	Productivity and efficiency higher than conventional still	Higher yield	[97]
17	Multi-cavity built-in condenser	Net daytime productivity increases up to 44.8%	Up to 44.8%	[98]
18	Rhombus mesh fins	Productivity enhancement reported	33.7%	[99]
19	Charcoal balls	Enhanced distillation productivity reported	Enhanced evaporation	[100]
20	Hemispherical stepped basin + PV heaters	Productivity enhancement reported	86.9%	[101]
21	Wick + baffles + PV heating	Productivity increase: 258%	258%	[102]
22	Evacuated tube collector + hemispherical still	Daily yield: 5.6 L m^{-2} (unit/time basis should be checked)	About 5.6 l/m^2	[103]

The above reviewed studies have demonstrated that productivity of solar stills can be improved by the optimization of heat transfer, increasing the evaporation area, optimization of condensation and thermal storage, and hybrid use of energy. Moderate improvements with simplicity of the system are achieved in the passive modifications like fins, reflectors, structures of a wick and stepped absorbers. Most often, the effects of more than one enhancement mechanism (thermal storage, auxiliary heating, photovoltaic assistance, or active cooling) are achieved, and these effects are greater. All of these improvements can lead to greater system complexity, energy consumption and cost though. Therefore, the most practical direction is to combine efficient evaporation and condensation enhancement with simple thermal-storage strategies, achieving higher freshwater productivity without compromising economic feasibility and operational reliability.

10. Conclusions

The present review aimed to explore recent advances in solar still development with a specific emphasis on design modifications, heat-transfer enhancement, thermal storage, nanomaterials, and hybrid systems. The investigated studies demonstrated that it is

possible to increase the productivity of the still in terms of freshwater by improving evaporation and condensation processes, maximizing the evaporation surface area. Optimizing thermal energy use.

The key finding of the present review consisted of the comparison of the recent advancements in enhancement techniques considering the impact of operating conditions, as well as the baseline configuration. Indeed, the suggested methods' impact on the productivity of solar stills varied significantly depending on the solar irradiance, water depth, condenser geometry, condensation conditions. Combination of enhancement techniques. Thus, the improvement in performance should be considered in relation to the operating conditions in which the solar still was tested rather than relying on the indicated percentage increase.

In general, the optimization of solar stills should be focused on the maximal freshwater productivity per energy input with the consideration of additional parameters, including cost, reliability. System complexity. The next generation of solar stills should rely on the comparative analysis and standardized operating conditions that would allow for assessing the enhancement techniques' efficiency in terms of energy and exergy performances, economic viability. Long-term reliability.

11. Future Recommendations

Further investigations should be carried out in order to incorporate the thermal storage with improved evaporation and condensation surface into the solar still systematically, especially by using the nano-enhanced PCM in the various solar still configuration. Additional experimental research is required to determine the proper concentration of nanoparticles, storage configuration and under various climatic and operation conditions. Long-term studies for the material stability, salt accumulation, durability, energy consumption and economic aspects are also recommended in order to promote the practical implementation of the solar stills which are reliable and have low complexity.

Nomenclature

ANN	Artificial Neural Network
Al_2O_3	Aluminum oxide
CuO	Copper (II) oxide
GBD	Global Burden of Disease
IHME	Institute for Health Metrics and Evaluation
NF	Nanofluid
NPCM	Nano-enhanced Phase Change Material
PCM	Phase Change Material
PV	Photovoltaic
PV/T	Photovoltaic/Thermal
QD	Quantum Dot
TEC	Thermoelectric cooling/device

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