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Impact of various environmental parameters and production enhancement techniques on direct solar still: A review

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ABSTRACT

People who live in isolated coastal locations currently struggle to find clean drinking water in many areas. There are a number of ways to obtain pure drinking water; however, the solar still (SS) remains the most effective one due to its affordability, environmental friendliness, and straightforward design. The conventional SS must be modified using alternative techniques because it has a lower production yield despite being cost-effective. In this context, the goal of this study is to review the published articles pertaining to the incorporation of various performance enhancing approaches into direct SSs for the generation of fresh drinking water, including nanoparticles, nano-PCM, hybrid nanoparticles, fins, and sponges. Reviewing the publications findings indicates that the production of fresh water is greatly increased by using hybrid nanoparticles and copper balls with PCM (4460 ml/m^2-day). Additionally, the sponge and aluminium absorber plates contribute to a 10%, and 30% improvement in productivity, respectively. The study also discusses potential areas for future research as well as challenges and opportunities for applying the SSs in developing nations. It is important to look at the studies of SSs in the areas of sustainability, exergy, exergo-economics, and energy as well as the characterization of hybrid nanoparticles. Future research is also necessary into the application of various PCMs with nanoparticles, hybrid nanoparticles, and carbon nanotubes.

1. Introduction

Global fresh water demand is roughly 4600 km^3/year and it is expected to be increased by 20–30% around 2050 [1,2]. Water scarcity impacted the water supply in Cape Town on March 13, 2018 and left 3.7 million residents without fresh tap water [3,4]. It is estimated that around one billion people on earth are suffering from the drinking water crisis [5], and contaminated water poses a serious threat to mankind [6]. Asian countries have 36% of the world's available freshwater reservoirs, and over 60% of the world's population is at risk of facing a fresh water crisis in the future [7]. Drinking of contaminated water is responsible for 80% of all diseases in the world [5]. Although two-thirds of the world's surface is covered by water, only 3% of the available water is usable for drinking and domestic usage [8]. Therefore, the most promising solution to this water shortage is the solar distillation technique to purify brackish or salty sea water. However, the solar still (SS) or desalination process suffers from its lower productivity and reliability in supplying water demand as required [9-11]. As a consequence, investigators have made continuous efforts for further improvement of the desalination techniques so that they can be implemented around the world more efficiently. Diverse desalination and water treatment technologies have been technologically advanced, including thermal expertise (by means of multi-stage flash-MSF and multi-effect desalination-MED), membrane expertise (by means of reverse osmosis-RO, and electro-dialysis-ED) [12]. Membrane technologies can effectively be utilized in water treatment processes [13-15], and UV-based advanced oxidation processes can be used to treat contaminated water [16]. The UN estimates the lowest annual per capita fresh water consumption at 1000 m^3 [12]. The desalination technologies consume 5 tons of crude oil to produce 1000 m^3 fresh water, which releases about 10 tons of CO_2 or about 5000 m^3 of greenhouse gases (GHGs) into the atmosphere [17]. In order to combat the energy shortages of recent centuries, renewable energy resources, which rely on natural resources to produce an endless supply of sustainable, non-polluting energy have gained significant importance as a viable alternative to conventional energy resources [18,19].

In recent years, tremendous research activities have been reported

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on the advancement of solar desalination. Solar-driven interfacial water evaporation technology is broadly considered a novel sustainable solution for the treatment of hyper-saline brine to resolve global water scarcity [20-22]. Mustakeem et al. [23] examined the MXene-coated membrane distillation process for stand-alone application and registered a system efficiency of 65.3%. The adsorption desalination (AD) process has also been analysed for treating high-saline water using low-grade solar energy and waste heat, which offers even more efficient solutions when hybridized with other desalination processes such as the MED cycle to enhance the overall production rate [24].

Fig. 1 shows the energy requirements of the main desalination processes [17]. Fig. 1 demonstrates that the mechanical vapor compression (MVC) desalination techniques consume more electrical energy, whereas multi-effect desalination-thermal vapor compression (MED-TVC) and the MED process use the least electrical energy.

The main benefits of the SS are low energy requirements, low investment costs, low maintenances and being ecologically friendly; however, the productivity per unit area of the SS is significantly lower than that of the other desalination processes [17]. The frequent parameters affecting the performance of the SS consist of insulation thickness, humidity, ambient temperature, wind velocity, water depth in the basin, basin material, solar radiation, and inclination angle, as reported in Fig. 2. The problems associated with lower productivity can be reduced, and the thermal performance of the SS can be enhanced either by modifying the design of the SS or optimizing the operating conditions [2]. Numerous improvements have been attained by additional fins [25], slope angle [2], cover cooling [26], sponge [27], internal and external reflectors [28], phase change material (PCM) [29], etc. Therefore, this research is intended to search for more suitable modifications and techniques to improve the productivity of fresh water in SS. Additionally, the production of SS is influenced by a number of variables, including solar intensity, free surface area of water, ambient temperature, water–glass temperature difference, wind speed, absorber plate area, temperature of incoming water, glass angle, and water depth [29-31]. The rest parameters (the free surface area of water, temperature of inlet water, glass angle, absorber plate area, and depth of water) can be adjusted to improve the productivity of the SS [32]. This study considers numerous factors and design modifications affecting the productivity of the SS.

Utilizing wick or sponge materials accelerates evaporation, raising the freshwater production rate. Abu-Hijleh et al. [33] provided a modified approach to increase the productivity desalination and reported that employing sponges cubes enhanced the distillation yield by 18%. They did this by adding sponge cubes on top of the water's surface. Jute cloth was used in a study by Shukla et al. [34] to enhance the evaporation process. Hassan et al. [35] used phage change materials along with a passive internal condenser and glass plate condensation in a stepped SS and found the production yield was boosted by 5.2 kg/m^2/day. According to Elsheikh et al. [36] the modified distiller's maximum daily distillate production was 3920 L/m^2. A number of statistical techniques were used to compare the predicted results from the two models. LSTM-MFO fared better than standalone LSTM for every measurement. For both solar distillers, the determination coefficient of the projected data using LSTM-MFO attained a high value of 0.999. Tiwari [37] conducted a thorough of the evaporation mass transfer coefficient of a passive single-slope in order to ascertain the effect of water depths. Tanaka et al. [38] investigated the impact of both internal and external reflectors on the distillation output of a single-slope basin-type still in addition to the quantity of solar radiation absorbed by a basin liner. Results found that the production rate was 21% higher than conventional SS throughout the year. Furthermore, Abdulateef et al. [39] determined the fin-nanoparticle configurations in a PCM-based thermal energy storage heat exchanger unit. The outcome of the experiment of Kabeel et al. [40] demonstrates that the traditional pyramid solar panel still produces the largest amount of 4.02 L/m^2/day, while the hollow utilizing fins increases production to 5.75 L/m^2/day, a 43% increase in daily productivity. The PCM addition upsurges productivity to 8.1 L/m^2/day or a 10.50% increase in daily productivity. Panchal et al. [41] used MgO and TiO_2 nanofluids in a stepped solar still and found that the distillate output was increased by 45.8% and 20.4% using MgO nanofluid and TiO_2 nanofluid, respectively. When using nanoparticles combined with black paint, a 10% and 12% upsurge in the temperature of the water and the absorber, respectively, were observed [42]. In another study, Sharshir et al. [26] employed copper oxide and graphite micro-flakes to enhance the SS production, and experimentation results suggest that distillation output was increased by 44.91% and

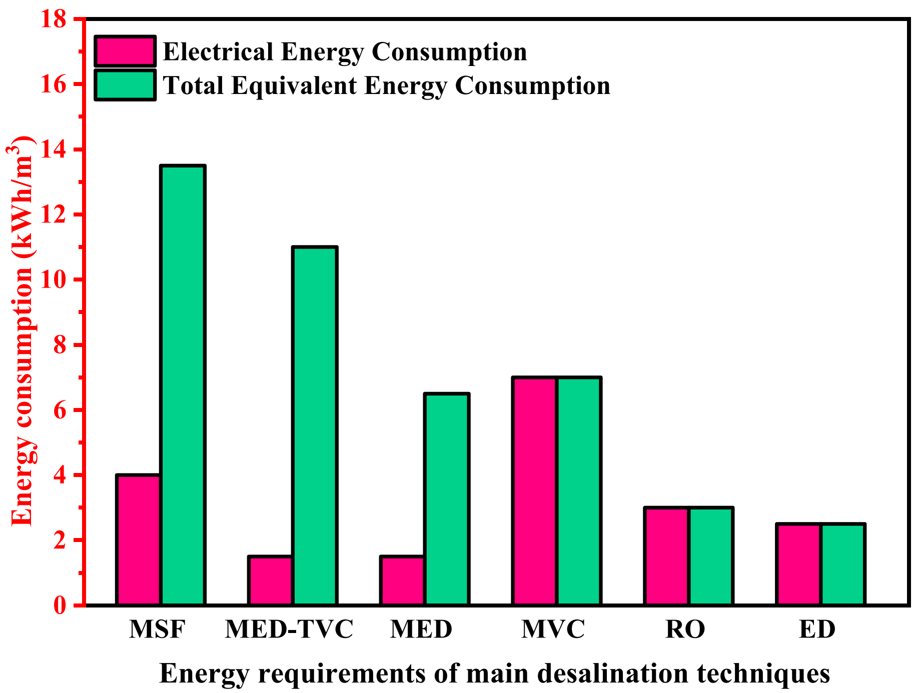

Fig. 1. Electrical energy consumption of different desalination techniques [17].

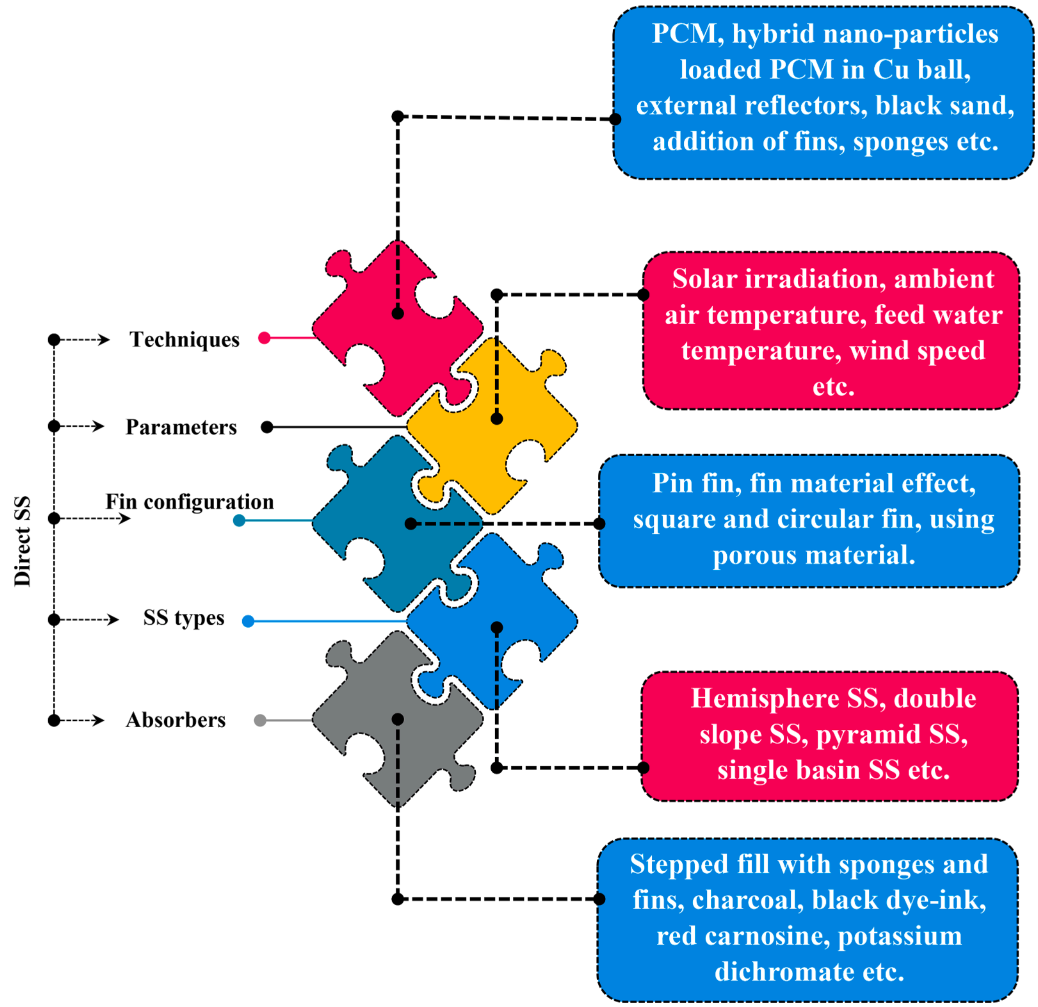

Fig. 2. Increasing the freshwater productivity of direct SS using different types of factors.

53.95% compared to conventional SS using copper oxide and graphite micro-flakes, respectively. In a double-slope SS, basalt rocks, concrete bricks, and crashing rocks were employed in three different ways to boost water production by Al-Doori [43], and results demonstrate that concrete bricks increased water production by an astounding 42%. Kannan et al. [44] used PCM-encapsulated cans in square and triangular designs and reported that substantial benefits can be achieved using PCM. In an experimental study, Tuly et al. [2] investigated the combined effects of an internal side wall reflector, hollow circular fins, and PCM and reported that productivity was enhanced by up to 51.8% compared to conventional one, whereas nanoparticles mixed with PCM resulted in further enhancement of 21.5%. In accordance with Moustafa et al. [45], a modified tubular solar still generates an average cumulative water output of 3.41 L/m^2/day, a 31.85% increase over the traditional tubular sun still's 2.58 L/m^2/day average. The improved tubular solar still has a daytime energy efficiency of 38.61%, whereas the traditional one only has a daytime energy efficiency of 30.67%. According to Alsaiari et al., the estimated root mean square deviation values for the MLP, MLP-GA, MLP-PSO, and MLP-ARO models are 130.79, 57.07, 40.28, and 2.82 ml for all SS designs [46]. Ghandourah et al. [47] reported that the yield of CSS was 2.95 L/day, whereas the yield of PSSCAP was determined to be 4.5 L/day. A comparison analysis revealed that the corrugated sheet utilized as an absorber plate in the PSSCAP resulted in a 52.54% greater yield than in the CSS. Moreover, the average thermal efficiency was shown to be 45.5% for the PSSCAP and 31.5% for the CSS. According to study, the projected cost of a 1L yield for a PSSCAP and a CSS is 0.68 and 0.53 INR, respectfully. Manokara et al. [48] investigated the solar panel integrated SS system for meeting electric and fresh water demand and reported that the highest energy and exergy efficiencies with insulation were 71.2% and 4.5%, respectively. Alsaiari et al. [49] noted that the JPT nanocomposite had a 40–60 nm particle size range and a porous structure with 85% crystallinity. A novel hybrid nanofluid (CTS) is created by combining the nanocomposite with cobalt (II) chloride ($COCl_2$), thiourea (CH_4N_2S), and silicon dioxide (SiO_2) at ratios of 10%, 20%, 30%, 40%, 50%, and 60%. The PSBSS basin was filled with CTS-filled silver-colored steel balls at regular intervals to improve the still's internal heat transmission mechanism. The high productivity of 8.7919 L/m^{2}day of the PSBSS with nanocomposites (0.3%) and nanofluids (40%) filling the silver-colored steel balls (JPTCTSS) is 50.55% greater than that of the conventional solar still (CSS) with nanofluid and the salty water in the basin. As stated by Ghandourah et al. [50] in terms of energy efficiency, water productivity, and energy efficiency, ALSS outperformed PCSS in thermal performance. PCSS and ALSS had average energy and energy efficiency of 2.30%, 42.40%, and 3.44%, 48.80%, respectively. For PCSS and ALSS, the highest distillate output was 3.40 L/m^2/day and 3.80 L/m^2/day, correspondingly. When compared to the SS without any thermal energy storage, Banoqitah et al. [51] found that the SS employing nano composite PCM and PCM without nano additions are boosted by around 75.65% and 114.81%, respectively, based on their experimental findings of producing fresh water. Elsheikh et al. [36] demonstrated that the modified distiller's maximum daily distillate production was 3920 L/m^2. A number of statistical techniques were used to compare the predicted results from the two models. LSTM-MFO fared better than standalone LSTM for every measurement. For both solar distillers, the determination coefficient of the projected data using LSTM-MFO attained a high value of 0.999. Elsheikh et al. [52] demonstrated that the MSS outperformed the CSS in terms of daily freshwater output, energy efficiency, and exergy efficiency by 34%, 34%, and 46%, respectively. The MSS has a manufacturing cost of 0.015 $/L per liter. Ghandourah et al. [53] demonstrated that, at a saline water flow rate of 0.05 kg/min, the daily productivity of the planned DSWSD coated with and without 20 wt% $LaCOO_3$/black paint is 5.40 and 3.85 kg/m^2/day, respectively. Furthermore, compared to the solar distiller without $LaCOO_3$/black paint, the average values of the convective and evaporative HTCs and energy efficiency are found to be greater by 11.20%, 17.54%, and 24.86%, correspondingly. Abulkhair et al. [54] discovered that the third system's yield had improved by 76.9% in comparison to the traditional system, and that its thermal efficiency and exergy efficiency had grown by 101.5% and 109.7%, respectively. Ultimately, employing the last method instead of the standard one results in a 29.7% reduction in the cost per liter of the overall yield. Sharshir et al. [55] studied that using nanotechnology such as ZnO nano-rod shapes in tubular SS, the output and efficiency were increased by 30% and 38%, respectively. Numerous factors [56], including biological health [57], the generation of energy and food, industrial and commercial output [56], ecological balance [56,58], and other applications [56], all show a strong correlation between access to fresh, clean water resources and human survival as well as societal growth. Through spontaneous phase transition of water in the atmosphere, the natural evaporation and transpiration process (such as plants) remove enormous volumes of water from rivers, lakes, seas, and lands, delivering water to the entire planet [59-62]. Moreover, numerous technologies for practical application of SS, such as thermal distillation, reverse osmosis, membrane filtration, electrodialysis, and photocatalysis, have been investigated in order to provide access to sufficient volumes of clean water to fulfill the expanding demand [63-69].

1.1. Bibliometric analysis

In addition to the literature overview, the authors undertook a bibliometric study to provide a comprehensive and data-driven view of scientific research in the field of solar desalination. Bibliometric analysis represents a quantitative approach that employs statistical and mathematical methodologies for the examination of publication and citation data [70]. It offers an objective and numerical assessment of research output, impact, and patterns. It enables the scrutiny of a substantial volume of literature, often encompassing extensive time periods and numerous publications. It provides a broader overview of the research landscape, including trends, patterns, and relationships between publications. The Scopus database was utilised for the literature search, which was restricted to relevant English-language journal articles. As a result, 1554 documents matching the filtering criteria were considered for the bibliometric analysis. In this study, VosViewer software [71] as well as the Biblioshiny tool [72] were employed to perform the bibliometric analysis. The network visualisation map of the keyword "Solar desalination" as used by the authors in their title, abstract, or keywords by co-occurrence cluster is shown in Fig. 3(a).

Fig. 3(b) depicts another interesting piece of information concerning the co-authorship analysis between countries. According to the

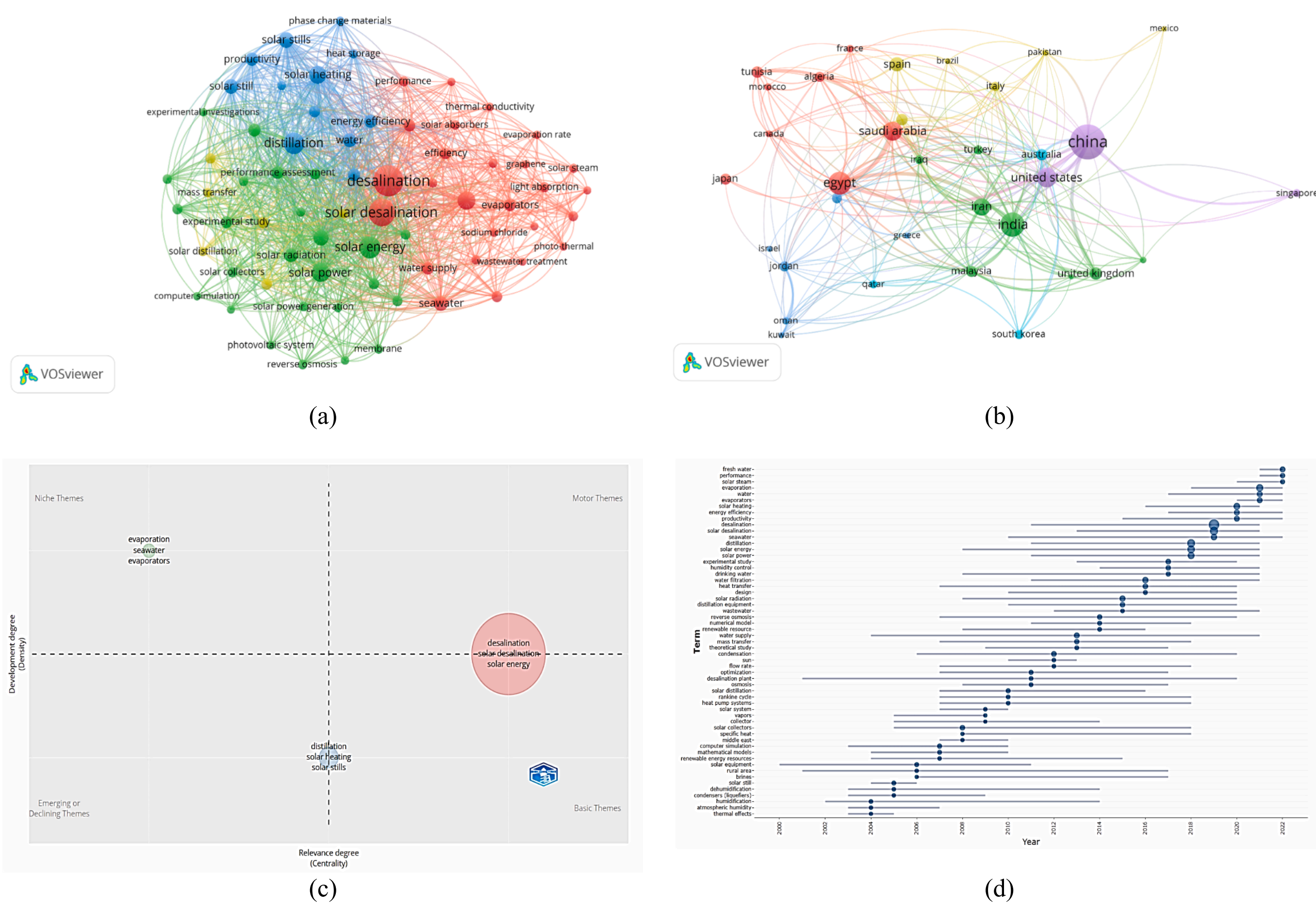

Fig. 3. (a). Network visualisation map of the keyword "Solar desalination" as used by the authors in their title, abstract, or keywords by co-occurrence cluster, (b) network visualisation map depicting the collaborative network of countries related to the research topic, (c) thematic visualization map, (d) trend topics from 2004 to recent times.

database, authors from 34 countries contributed to the literature. China has the most publications and collaborations with other countries, with 432 documents, followed by India (211), Egypt (187), the United States (136), Saudi Arabia (131), Iran (110), and the United Kingdom (56).

Thematic maps offer an impartial approach to categorizing keywords into clusters based on their degree of development (density) and relevance (centrality) [73] as illustrated in Fig. 3(c). The visual representation of this thematic map effectively depicts four distinct themes: motor (located in the top right quadrant), niche (situated in the top left quadrant), emerging or declining (found in the bottom left quadrant), and basic themes (located in the bottom right quadrant). The centrality quantity quantifies the level of connectedness between topics and thus their significance in a specific field. Fig. 3(d) illustrates the trending topic analysis conducted using the author's keywords from the dataset. During the analysis, the following parameters were configured: a time-span ranging from 2004 to the present year, a minimum word frequency of 5, and a limit of 5 words per year.

1.2. Research contributions

The main objective of this article is to provide an extensive and detailed review of the recent advancement techniques used in the SSs to improve freshwater production. In this review process, special focus has been given to the utilization of nanoparticles and hybrid nanoparticles with thermal storage to improve the reliability and production yield of the solar stills. This study outlines a systematic review of the SSs, including the impacts of environmental parameters, operational characteristics, and design characteristics on their performance. Therefore, this review article evaluates the production of distillation rate using different modification techniques and criteria, such as PCM, hybrid-nanoparticles, hybrid-nanoparticles loaded PCM in copper balls, integration of storage tank, external reflectors, black sand as sensible heat storage, addition of fins, sponges, integration of the PV panel, absorber plate, charcoal particle packed layer, jute cloth, wick materials, etc. This updated review will provide different approaches to developing highly efficient and reliable SSs. Finally, this article discusses the benefits and limitations of these techniques and provides the future direction of research and applications of SSs.

2. Environmental parameters affecting the freshwater productivity of direct SS

The performance of the SS is affected by factors such as solar irradiation, ambient air temperature, basin absorptivity, dust and cloud cover, and relative humidity. In accordance with the weather, it is also raising or lowering the yield rate.

In this section, these factors are briefly and in-depth discussed:

2.1. Solar irradiation

The vital factor influencing still-productivity is solar radiation [74]. Investigational research on the relationship between solar radiation intensity and still efficiency was done by Nafeya et al. [30]. According to their findings, productivity increases as solar radiation intensity rises, and this impact is most noticeable during the summertime. Additionally, Almuhanna et al. [75] have also suggested that the rate of distillate production rises when solar radiation levels are rising. However, Morse and Read [76] employed the analytical formula to determine the impact of numerous factors, notably solar radiation, on the distillate yield of the SS. Remarkably, numerous research has been accompanied to examine the impact of solar radiation on stills, and it has been discovered that production rises proportionately with solar radiation. The output indicates that the yield will enhance as the rate of energy transfer increases.

2.2. Ambient-air temperature

The ambient temperature has considerable effects on the production yield. In this context, Nafeya et al. [30] investigated how changes in ambient temperature affected SS, and the findings indicated that raising the ambient temperature by 5 °C could only slightly enhance production, by the range of 3%. The consequence of surrounding temperature on daily production was examined by Alheefi et al. [77]. Without any alteration, the assessment was done in a SS, and the results showed that the greatest recorded vapour temperature, which happened around 13:00, was only about 67 °C. According to this investigation, the highest reported cover temperature happened between 13:00 and 15:00 PM. Al-Hinai et al. [78] quantitatively examined basic SS production using a computer program and found that productivity increased by up to 8.2% with a 10 °C increase in ambient temperature from 23 °C to 33 °C. Fig. 4 displays the impact of the daily average ambient temperature on the daily water output. In this experimentation process, the atmospheric temperature and production yield have been calculated on an hourly basis for three consecutive days.

2.3. Feed water temperature

Since the temperature of the water in the basin is a determining factor in the production of SSs, preheating the water before supplying it to the basin will improve its productivity. Alawee et al. [79] improved the output of a pyramid type-SS by about 214.0% by using a PV panel to warm the water in the basin and installing spinning cylinders driven by a PV panel to lessen the thickness of the evaporation layer within the basin. A three-stage process was utilized by Abdullah et al. [80] to enhance the efficiency of a conventional SS, including water heating, a rotating drum inside the basin still, and an external condenser. The production was increased by 300%, according to research observations. When a solar pond and SS are combined, Panchal et al. [81] investigate the effects and discover that heated water sent to the basin greatly increases productivity. El-Sebaii et al. [82] examined an active SS single basin and a shallow solar pond (SSP) and found that the production was 5.74 kg/m^2/day as opposed to 1.830 kg/m^2/day without the SSP. According to research conducted [83], the yearly average production and efficiency of the still with and without SSP were determined to be correspondingly 52.36% and 43.80%, respectively.

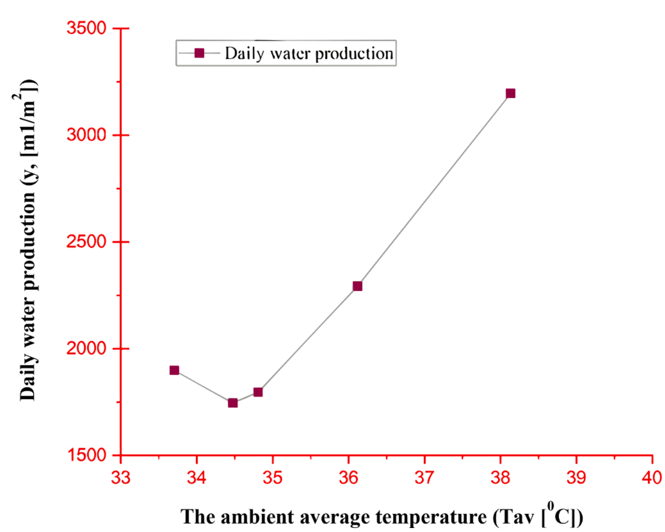

Fig. 4. Daily water production in the SS on the basis of ambient average temperature [77].

2.4. Wind speed

The increase in wind speed results in higher productivity, according to Garg et al. [84], Copper [85], and Soliman [86]. Meanwhile, Hollands [87] and Yeh and Chen [88] found that wind speed increments result in lower output. Additionally, Morse and Read [76] claim that wind speed has little or no effect on output. According to a scientific investigation, production only rises with increasing wind speed below 4.5 m/s; above that point, it stays the same. El-Sebaii [89] carried out a study to determine the necessary wind speed. Researchers chose 10 m/s for normal summer days and 8 m/s for winter days for their inquiry. Beyond the critical limit, the production declines as the wind velocity rises steadily. They added that for optimal yield, the wind velocity's magnitude would change based on the geometrical design of the SS, the water's ability to store heat, and other factors. Castillo-Tellez et al. [90] carried out an experiment using DSSS linked to a wind tunnel at varied wind speeds of 2.5 m/s, 3.5 m/s, 5.5 m/s, and 6.9 m/s. They found that the total output rose by 62.3% with increments in wind velocity ranging from 2 to 5.5 m/s. 5.5 m/s is the ideal wind speed at which researchers concluded their study. According to their analysis, the ideal wind speed for output to rise is 5.5 m/s; above this wind speed, output begins to decline. This is because an increase in wind velocity results in a decrease in evaporation heat transfer. El-Sebaii [91] also discovered that productivity increases as the wind velocity rises up to a specific point known as the critical wind velocity (for summer: 10 m/s and for winter: 8 m/s) before yield starts to decline.

2.5. Dust and cloud cover

Dust accumulation on the glass cover results in a reduction in transmittance, which causes the incident solar radiation to be lost [92]. El-Nashar [93] conducted a study to examine the effects of dust accumulation on the output of evacuated tubes in flat-plate collectors. Glass transmission decreased 6% in the winter and 10% in the summer, and the collector's transmittance decreased by around 70% yearly when left unattended and uncleaned [94]. The impact of the dust coating advances rather quickly within the first 30 days of interaction, according to research by Hassan et al. [95]. According to their research, productivity drops by 33.5% in the first month and climbs to 65.8% without panel cleaning over a six-month period. These results will undoubtedly vary according on the location and dust clouds are commonly observed in arid or deserted locations. The effects of dust gathering were investigated by Hottel and Woertz [96] in Boston, Massachusetts, and the results showed that the glass cover had been coated with ashes at a tilt angle of 30°, which resulted in a usual loss of incident solar energy of 1%. Zamfir et al. [97] undertook an investigation to determine the impact of clouds on a collector's monthly average output and discovered that productivity is lower on average overcast days than on ordinary days.

2.6. Relative humidity

Improvements in relative humidity help to boost system yield, according to research by Koffi et al. [98] that looked at the mean humidity of 65% during wet weather and 40% to 55% during dry weather. Mohsenzadeh et al. [99] investigated the impacts of humidity and aspect ratio on the convective heat transfer and productivity of SS and found that higher output is attained with lower humidity and a larger aspect ratio of the SS. The authors reported that the SS with a relative humidity of 62% produced fresh water of 3.49 kg m^{-2} day^{-1}.

3. Different techniques to improve the productivity

Different methods and criteria are employed to boost the production of fresh drinking water in SS, including the use of PCM, hybrid-nanoparticles, PCM loaded with hybrid-nanoparticles in copper balls, the integration of storage tanks, external reflectors, black sand as sensible heat storage, the addition of fins, the use of sponges, the integration of PV panels and PV collectors, absorber plates, etc., which are briefly described here:

3.1. Phase change materials (PCM)

The integration of thermal energy storage (TES) using PCMs into the SS improves productivity [100]. Besides, the latent heat characteristics allow PCM to store and produce a tremendous quantity of heat as thermal energy [101,102]. Subsequently, because the majority of PCMs, particularly organic ones, are susceptible to simple leakage during the process of solid–liquid phase shift, it is important to surround them with a supportive matrix, creating PCMs with shape stability [103,104]. In addition to high thermal conductivity, stable shape and strong sun absorption are required characteristics of the shape stability phage change materials (SSPCM) [105]. The performance of two weir-type cascade SSs with and without PCM storage on bright and partly overcast days was quantitatively examined by Sarhaddi et al. [106]. According to the findings, the daily productivity of the still with PCM (7.05 kg m^{-2} day^{-1}) was marginally greater than that of the SS with PCM (6.63 kg m^{-2} day^{-1}) on sunny days. On the contrary, the daily productivities for the SSs with and without PCM were 4.94 kg m^{-2} day^{-1} and 3.84 kg m^{-2} day^{-1} respectively, on a partly overcast day. Regardless of the better performance of using PCM in direct solar still to enhance productivity and efficiency, there are a few drawbacks with PCMs, such as their lower thermal conductivity, which results in a slower heat transfer rate in solar still, which can decrease the overall efficiency of the system. Furthermore, the repeated cycling of PCMs between solid and liquid in solar still can lead to degradation and aging, reducing their long-term performance and reliability [107]. Thus, PCMs with better heat transfer characteristics can be used in SSs, and a long-term performance investigation is required to assess the overall performance. There are several varieties of PCM, including commercial grade-paraffin wax, beeswax, coconut oil, stearic acid, linoleic acid, lauric acid, capric acid, palmitic acid etc., and the performance of these PCM in SS is illustrated in Table 1.

3.2. Nanoparticles

Nanoparticles show high thermal conductivity [122]. Several studies represent varying outputs of nanoparticles using PCM to increase the thermal conductivity. The best addition for improving the heat transfer of paraffin is GR [123]. To improve the thermophysical characteristics of the brackish water, copper oxide and graphite nanoparticles have been introduced to the basin of a traditional solar still [124]. When graphite and copper oxide were utilized in place of standard materials, the overall output of the solar still rose by approximately 41.18% and 32.35%, correspondingly [125]. On the contrary, TiO_2 is more effective than the other nano-additives in altering the heat conduction and thermal storage performance of paraffin [126]. Moreover, a maximum enhancement of 19% was observed for CuO based PCM at 70 °C [127]. By including copper oxide nanoparticles into the modified solar still basin with a thermoelectric cooling channel, the overall freshwater production was increased by around 81%. The thermoelectric module plays a crucial role in lowering the temperature of the glass cover, which in turn improves the condensation process and the flow of humid air inside the solar still trough [124]. This is why the modified solar still's overall yield increased more than that of the original one. When aluminum oxide was added to the salty water, the stepped solar still's hourly freshwater production increased by around 22% [128]. According to Essa et al. [129], the productivity of the TDSS coated with nanoparticles was 6650 ml/m^2.day, whereas the CSS produced 2800 ml/m^2.day, an increase of 137%. However, the thermo-physical characteristics of nanoparticles, for example, density, thermal conductivity, etc., are represented in

Table 1
Summary of several varieties of PCM using in SSs.

SS type	Study area	PCM used/wick material	Findings	References
Double-slope SS		Black rubber, black ink and black dye	The output of the SSs was improved by about 38%, 45% and 60% by the accumulation of black rubber, black ink and black dye, respectively.	[108]
Stepped SS		Paraffin wax	The SS with LHTESS realised a total daily output of almost 4.6 L m^{-2}.	[109]
Single-slope, single-basin SS	Jeddah, Saudi Arabia	Stearic acid	On a summer day, the PCM enhanced the daily output of SS by 80.12%.	[110]
Triangular pyramid SS	Chennai, India	Paraffin wax	The output of the SS with LHTESS was 28.57% and 47.83% higher than that of without LHTESS in summer and winter, respectively.	[111]
Single-slope, single-basin SS		Lauric acid	By means of PCM improved the distillate assortment of the SS by 36%.	[112]
Single-slope SS	Wuhan, China	Paraffin wax with nanoparticles	The existence of PCM and FGN improved the output of the SS via 73.8%.	[113]
Single-slope SS	Tanta city, Egypt	Some organic and inorganic PCMs	The capric–palmitic and organic PCM A48 have the benefit of high output.	[114]
Concentrator-coupled hemispherical basin SS		Commercial grade paraffin wax	Thermal storage augmented the daily output of the concentrator-coupled hemispherical basin SS via 26%.	[115]
Cylindrical parabolic concentrator with a focal pipe–coupled SS		Paraffin wax	The daily freshwater output of the established SS was 140.4% higher than that of the conventional SS in average.	[116]
Multi-wick double slope and single slope SS	Prayagraj, India	Jute wick	Energy efficiency of SS for single slope was 23.93% and for double slope SS is 28.78%.	[117]
Tubular SS	Berket-elsabaa city, Menoufia, Egypt	Pure paraffin wax, black wick,	Maximum energy and exergy efficiency improvement of the SS were 82.16% and 221.8%, respectively.	[118]
Stepped SS	Kafrelsheikh, Egypt	Paraffin wax	Productivity of the SS increases 55% and average daily thermal efficiency is 46–52.4%.	[119]
Trays SS	Saudi Arabia	Paraffin wax	Thermal efficiency of the SS is 51.5% and the accumulated productivity is 5.0 L m^{-2} day^{-1}.	[120]
SS with condenser and solar collector		Coconut oil	1. By means of both condensers and profited from radiative cooling, formed 31.2% more freshwater than via only the air condenser was cast-off. 2. The PCM condenser unaided had no water yield and condensation happened only inside the air-condenser.	[121]

Table 2
Thermo-physical characteristics of nanoparticles.

Author	Nanoparticles	Density	Thermal conductivity	Particle size
Tuly et al. [2]	Al_2O_3	3900 kg/m^3	46 W/m K	10–14 nm
Yavari et al. [139]	Graphene	–	4840–5300 W/m K	–
Yang et al. [140]	Nano-Si_3N_4	–	17.6 W/m K	–
Wanatasanappan et al. [141]	CuO	6390 kg/m^3	–	<50 nm
Said et al. [142]	TiO_2	3900 kg/m^3	8.4 W/m K	5 nm
Mousavi et al. [143]	ZnO	5600 kg/m^3	–	30 nm
Kabeel et al. [144]	Cu_2O	6320 kg/m^3	76.5 W/m K	10–14 nm
Sathyamurthy et al. [145]	MgO	3585 kg/m^3	48.4 W/m K	–
Kabeel et al. [132]	Graphite	1770 kg/m^3	195 W/m°C	–
Reddy et al. [146] and Sundar et al. [147]	Silver	10500 kg/m^3	425 W/m K	–
Reddy et al. [146] and Sundar et al. [147]	Nanodiamond	3100 kg/m^3	1000 W/m K	–

Table 2. Furthermore, paraffin-based nano-PCM is an outstanding thermal energy storage because its latent heat has risen by 20.67% and 78.89% as a result of the inclusion of Fe_3O_4 (5 wt%) and CuO (10 wt%) [130]. Additionally, various nanoparticles used in SSs are displayed in Table 3. Tuly et al. [131] investigated the modification of conventional SS by integrating nanoparticles in PCM, internal reflectors, fins, and collectors as illustrated in Fig. 5**(a)**. In this process, hourly temperature readings of various SS body segments, such as the exterior and inner glass surfaces, basin liner, ambient, basin water, PCM, and nano-PCM temperatures, were recorded using DS18B20 temperature sensors. A data logger system was connected to the various sensors to collect data. The result denotes that the utilization of nano-PCM increases the distillate yield by 92 % compared to the conventional case. The graphite nanoparticles and PCM are used as storage materials in different concentrations to improve the distillation output of a SS, as reported in Fig. 5**(b)** [132]. A comparative analysis of three different nanoparticles (i.e., TiO_2, Al_2O_3, and Cu_2O) has been investigated by Farouk et al. [133], and the outcome suggests that the Cu_2O-based offers maximum production yield than the TiO_2 and Al_2O_3-based nanoparticles. The schematic layout of their analysis is described in Fig. 5**(c)**. According to Naveenkumar et al. [134], conventional double-slope solar stills with 0.1% volume concentrations of CuO, Al_2O_3, and ZnO nanofluids have the highest increases in energy efficiency and exergy efficiency of 20.96%, 18.01%, 10.76%, and 52.53%, 38.52%, and 30.35%, respectively, when compared to conventional solar stills without nanofluid. Additionally, it demonstrates that using a water-cooled condenser, solar-operated vacuum fan, and 0.1% volume concentration of CuO, Al_2O_3, and ZnO nanofluids in a double-slope solar still increases both the maximum production rate and cumulative production by 59.26%, 55.56%, 51.85%, and 96.43%, 82.14%, and 75%, respectively, when compared to a conventional double-slope solar still, as illustrated in Fig. 6 [134]. To enhance the thermal characteristics of the base fluid and the efficacy of distilled water, several nanofluids, including CuO, Al_2O_3, TiO_2, graphene oxide, ZnO, and carbon nanotubes of various volume concentrations were utilized in the DSSS. Due to its dark color, which is a result of strong solar absorptivity, CuO nanofluid demonstrates the highest efficiency [135]. Sharshir et al. [136] compared the productivity using CuO nanofluid, Fe_2O_3 nanofluid, and cotton hanging pads with the

Table 3
Summary of various nanoparticles using in SSs.

SS configuration	Nanoparticles used	Findings	Year	References
Stepped SS	Fe_3O_4 and Graphene oxide	Daily distillate yield: 1577 g/day Production enhancement: 75% Daily energy efficiency: 12.3% Cost of water ($/L): 0.0188	2023	[148]
Hemispherical SS	Graphite -Sheep fat as PCM	Daily yield augmentation ratio: 95.5.2% Thermal efficiency: 61.7% Exergy efficiency: 5.8% Cost of water ($/L): 0.0106 Reduction in CO_2 emission: 6.27-ton CO_2/year	2023	[226]
Tubular SS	Nano-Co_3O_4 and aluminum shavings - PCM	Daily distillate yield enhancement: 24.56 % Average efficiency improved: 64.3 % Thermal properties of PCM improved: reducing > 50 min in the melting time.	2023	[227]
Vertical Wick Tubular Solar Still (VWTSS) with mirror	Ag nano	Productivity: 209 % greater productivity VWTSS (9900 ml/m^2) than CSS (3200 ml/m^2) Reduction in CO_2 emission 34.8 tons CO_2 per year. Cost of water ($/L): 0.014	2023	[228]
Tubular SS	CuO	Daily distillate yield: 6.65 L/m^2 Thermal efficiency: 63.8% Cost of water ($/L): 0.024 Payback period: 5 months	2022	[129]
Tubular SS	Graphene oxide nano-PCM	Daily distillate yield: 53.91% Daily energy efficiency enhancement: 116.5% Thermal conductivity improvement of nano-PCM than only PCM: 52%	2022	[149]
Trays SS	CuO nano-PCM	Daily distillate yield enhancement: 108% Daily energy efficiency: 47.14%	2022	[120]
Double slope SS	Al_2O_3 nano-PCM	Daily distillate yield: 84% Daily energy efficiency: 121% Daily exergy efficiency: 111% Cost of water ($/L): 0.0199	2022	[2]
Double slope SS	CuO nano-PCM	Daily distillate yield: 113% Daily energy efficiency: 112.5% Daily exergy efficiency: 190% Cost of water ($/L): 0.011	2021	[150]
Stepped SS	TiO_2(0.1%)	Daily distillate yield: 33.18% Cost of water ($/L): 0.016	2019	[151]
	MgO (0.1%)	Daily distillate yield: 51.7% Cost of water ($/L): 0.025		
Single slope SS	CuO nano-PCM	Daily distillate yield: 43.02% Cost of water ($/L): 0.13	2018	[152]
Stepped SS	Al_2O_3 nano-PCM	Daily distillate yield: 55% Daily energy efficiency: 38% Cost of water ($/L): 0.014	2016	[153]

conventional system and reported the highest energy efficiency was 51%, 45%, 34.5%, and 30% for the CuO nanofluid, Fe_2O_3 nanofluid, cotton hanging pads, and conventional system, respectively. As nanoparticles dispersed in the nanofluid may settle or agglomerate, leading to uneven distribution and reduced heat transfer efficiency within the solar still. This can impact the overall performance and productivity of the system [137]. ZnO nanorods have potential energy conversion applications [138], and graphene nanoplatelets can also be used as a cost-effective energy harvesting process [122].

3.3. Hybrid-nanoparticles

The output of fresh drinking water in SSs is improved with the use of hybrid nanoparticles. The inclusion of nanofluid boosted the yield of the SS because of the enhanced heat transmission properties of nanoparticles [154]. The thermo-physical properties of hybrid nanofluids are represented in Table 4. The thermal conductivity of copper balls is improved more than with traditional PCM in copper balls when hybrid nanoparticles are added, and the productivity of pure water is also improved. Moreover, the appropriate combination of hybrid nano PCM, or 75%:25%Al_2O_3-CuO, increased thermal conductivity by over 200% compared to conventional PCM [155]. As opposed to single nanoparticles loaded with PCM, several kinds of hybrid nanoparticles can be loaded with PCM to increase thermal conductivity. Nanofluids were introduced to de-ionized water in both classic and modified ways in order to take advantage of certain advantages of nanoparticles, such as their radiative property, high surface-to-volume ratio, and improved thermo-physical characteristics [156]. Moreover, hybrid nanofluids can greatly improve the thermal efficiency of heat generating systems [157]. The thermal conductivity of base fluid has been markedly boosted due to a hybrid of ferric oxide and multi-walled carbon nanofluid, which has significantly improved the heating system's thermal performance [158]. As compared to base fluid, hybrid carbon nanotubes and copper oxide nanoparticles effectively transport heat [159].

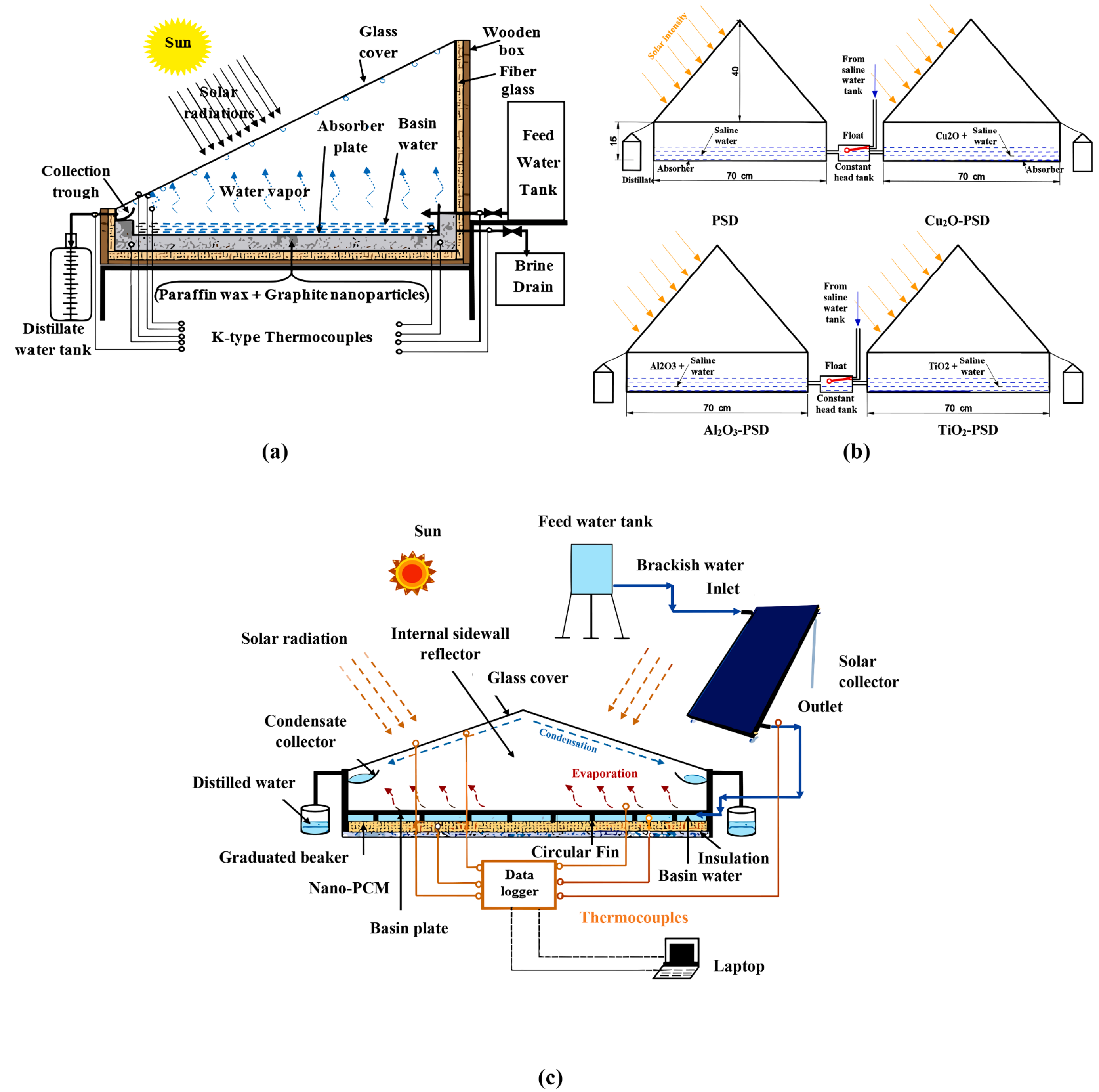

Fig. 5. (a). SS graphite nanoparticles mixed paraffin wax [132], (b). SS using three different nano-particles [133], (c). schematic layout of SS modified with flat plate collector, internal sidewall reflector, hollow circular fins, and nano-PCM [131].

3.4. Integration of storage tank

The efficiency of fresh drinking water is increased through storage tank integration. By maintaining the tank water temperature constant at various levels, Voropoulos et al. [165] examined the behaviour of a standard type SS combined with a hot water storage tank. The small SS-storage tank distillation system has been examined for many days at various tank water temperatures, including 70 °C, 60 °C, 50 °C, and 40 °C [165]. To maintain the tank water temperature almost constant and within the specified ranges, the heating installation is fitted with a temperature-control mechanism. The consequences of this experiment revealed that SS-storage tank systems produce more distilled water. By fusing the storage tank with the SS, the distillate output was able to remain consistent throughout the entire day. Due to higher basin water temperatures, adding a storage tank to a SS increases the yield of distilled water, but integrating a storage tank in a solar still system adds complexity and cost to the overall setup and may also require additional space.

3.5. External and internal reflectors

The installation of the external reflector improves the reflected radiation transmitted through the glass cover. The external reflectors are composed of extremely reflective materials, including mirror-finished metal plates [32]. Tanaka [166] conducted that on a tilted wick SS with an external flat plate reflector to establish the ideal inclination for

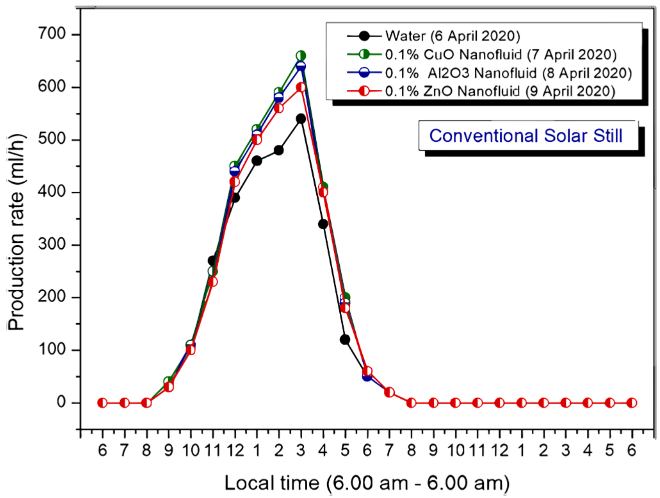

Fig. 6. Production rate of the modified SS with nano-fluid [134].

the reflector and SS for various seasons. The productivity may be increased year-round by an average of 21% by altering the inclination of both the still and the reflector in any season where the inclination angle of the reflector is less than 25°. Karimi et al. [167] examined whether installing internal reflectors (IRs) on every wall of a still may boost distillate output by 65%, 22%, and 34% throughout the winter, summer, and full year, respectively, compared to a still without IRs. Khalifa and Ibrahim [168] examined the output of a basin-type SS with an internal and exterior reflector slanted at angles of 0° (vertical), 10°, 20°, and 30° throughout the winter. According to an assessment of fixed and sun tracked SSs, the usage of sun-tracked SSs boosted production by around 22% as a result of a 2% boost in total efficiency. However, external reflectors used to increase solar radiation concentration can be challenging to position and align properly, requiring frequent adjustments to optimize performance. Internal reflectors within the solar still can suffer from degradation or discoloration due to exposure to high temperatures and prolonged exposure to UV radiation. This can diminish their reflective properties over time, reducing their efficiency in directing sunlight onto the water surface [169].

3.6. *Black sand as sensible heat storage*

Sand in the SS enhances productivity by 14%, according to research by Velmurugan et al. [170] who employed pebbles, sponges, black rubber, and sand in the fin-type single-basin SS to boost production. Srithar [171] increased the output of the single SS by adding sponge, pebbles, and sand and reported that sand and sponge together produced the highest production improvement of 32.32%. Additionally, Fig. 7 compares the production of three different types of stills (conventional still, yellow sand still, and black sand still) per hour. The findings clearly show that the SS with black sand has a significantly higher output than yellow and conventional stills. While black sand can absorb and store heat effectively, the transfer of heat from the black sand to the surrounding water in the solar still may be relatively slow, resulting in longer heat transfer times and potentially limiting the overall productivity of the system. Also, limited heat capacity may restrict the duration and efficiency of heat release from the black sand, particularly in periods of extended or high-demand operation [172,173].

3.7. *Addition of fins*

Fin addition increases water surface area, enhancing heat transfer rate, and may also be used to minimize bottom heat loss from SS. Adding fins is a low-cost heat transfer improvement technique. The use of square fins, whose contribution to the production of distillate water is minimal, increases its yield. When compared to a circular fin, Rajaseenivasan and Srithar [175] discovered that a square fin in a SS produced the most distillate. The production of stills is unaffected by the fin material. The daily productivity cost of stills can be decreased by means of fins in SSs. Utilizing various absorbent materials with fins will boost the still's production. While fins can enhance heat transfer by increasing the surface area available for heat exchange, they may also result in increased heat loss to the surroundings due to increased surface exposure. This may reduce the overall efficiency and productivity of the solar still [25]. Therefore, the optimal sizing and configurations of fin types and the selection of fin materials are very important for integrating fins

Table 4
Thermo-physical properties of hybrid nanofluids.

Hybrid nanofluids	Density	Dynamic viscosity (m.Pa.s)	Thermal conductivity	Specific heat	References
Al_2O_3-CuO (50:50)	1.0768 ± 0.0001 (g/cm^3)	3.531 ± 0.002	0.415 ± 0.001	3095 ± 25 (JKg^{-1}K^{-1})	[141]
Al_2O_3-MWCNT	–	10 wt% hybrid suspension demonstrations three times in the dynamic viscosity associated to water when the percentage of nanoparticles is raised up to 10 wt %.	Roughly 4% and closely 13% relative improvements in the thermal conductivity were established for the PCM suspension of 10 wt% is having the nanoparticles of 2 wt% and 10 wt%, correspondingly.	Compared to water, there was a 40% upsurge in the heat capacity of the 18.2 wt% particle mass fraction PCM suspension of currently melting particles.	[160]
Activated Carbon graphene composite (ACG)	The greatest density improvement is 0.09 percent for 0.06 wt% at 20 °C.	With 0.06 wt%, the maximum viscosity incensement of 4.16% was seen.	With 0.06% of the hybrid's weight contains activated ACG) in EG; at the same concentration, the thermal conductivity improvement was 4.17% at 20 °C and 6.47% at 40 °C.	Nanofluid at 0.06 wt% fewer than the base fluid at 50 °C was found to have a 2.25% greater specific heat capacity.	[161]
MWCNTs/Si O_2 (20:80)	–	Hybrid nano lubricants presented a maximum of 37.4% improvement in viscosity.	–	–	[162]
Ag–MgO hybrid nanofluid	–	At 0.02% volume concentrations, viscosity readings were around 24% higher.	The current model delivered higher Thermal conductivity readings and improvement over the models that are obtainable in the literature. The maximum boost of 8.6% was realized at 0.02% volume concentrations.	–	[163]
GNP-Ag nanocomposite	0.09% density rises via nanofluids with respect to water at a temperature of 40 °C.	In comparison with water at 40 °C, 30% increase in the viscosity.	Boost of over 17% at 20 °C utilizing 0.1% weight and the boost is around 22.22% at 40C.	–	[164]

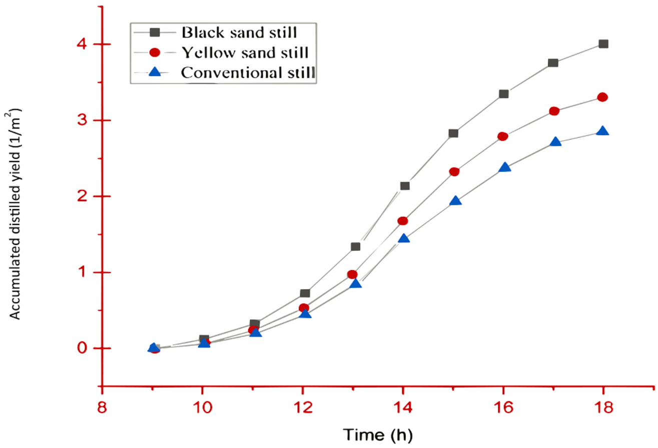

Fig. 7. Hourly variations of basin water and sand productivity for the tested SSs [174].

into the SS system. The summary of various fin types used in SSs and how they affect the performance of SSs is given in Table 5.

A crucial consideration when developing any solar thermal usage is heat transport. A simple tool called a fin may be cast-off in a SS to improve surface area. Heat transmission occurs as surface area increases. Fins have been utilized by investigators in the SS to improve water surface area and, subsequently, water temperature. The following is a discussion of various fin configuration parameters, including pin fins, fin materials, square fins, etc.

3.7.1. Pin fin used in SS

The research on traditional SSs using pin fins and condensers was conducted by Rabhi et al. [184] in three distinct scenarios: a normal SS, a modified SS with a pin fin, and a modified SS with a pin fin and condenser. In a modified SS with a pin fin and condenser, more distillate is produced as the pin fin increases the surface area, which raises the water temperature and enhances condensation via the condenser. In another study, Alaian et al. [177] compared the performance of a regular SS with a modified SS using a pin-finned wick and found that a pin-finned wick produced more freshwater (23%) than the regular SS.

3.7.2. Effect of fin materials

Fin material plays a very little role in distillate water production. The material of the fin has no appreciable effect on the productivity of the distillate water. El-Sebaii and El-Naggar [178] looked at the effectiveness of SSs using various fin materials and their findings suggested that changing the fin materials has no appreciable impact on the distillate yield.

3.7.3. Fin configurations

El-Sebaii et al. [179] investigated the impact of fin configurations on the SS. The authors employed a single basin SS with varied fin heights and fin thicknesses and reported that the output rose as fin number and breadth increased, as illustrated in Fig. 8.

3.7.4. Square and circular fin used in SS

In direct SS, circular fins are more beneficial and effective to employ. In the weather conditions of Chennai, India, Rajaseenivasan and Srithar [175] conducted an experimental examination of a single basin SS with square and circular fins and reported that square fins in SSs produced the most distillate. Additionally, they evaluated the economic study and carbon credit of SSs with fins. In another work, Jani and Modi [185] performed research work on a double slope SS to examine the impact of hollow fin shape and water depth. According to experimental findings, circular fins are more productive and efficient than square fins. Additionally, a 10 mm basin has a larger maximum water flow than a 20 mm or, 30 mm basin.

Table 5
Various types of fins used in SS.

Serial No.	SS with modifications	Fin's type	Findings	Reference
01	Modified single-basin single-slope SS with pin fins absorber and condenser.	Pin fin type	Higher absorber and glass temperatures are produced by a pin fin absorber with condenser than by a traditional still.	[176]
02	SS augmented with pin-finned wick.	Circular pin fin	The effectiveness of adding sunlight to pin-finned supplement may be increased to 23%.	[177]
03	Finned single basin SS.	Circular fin	Up to 16% more daily output and efficiency is provided by SSs with fins.	[178]
04	Fin configuration parameters with single basin SS.	Rectangular fin	The daily output still increases when fin height increases, however it drops as fin thickness and fin number rise.	[179]
05	Single slope SS integrated with a PCM-based pin-finned heat sink.	Hollow cylindrical fin	Compared to SSs with CSS and PCM, pin-finned solar stills with PCM provide productivity gains of up to 17% and 7%, respectively.	[180]
06	Fin type SS integrated with fin type mini solar pond.	Rectangular solid fin	Fin-to-fin SS integration boosts production by 50% compared to traditional SS.	[181]
07	Finned acrylic SS and galvanized iron SS	Square fin	The productivity of an aluminium finned SS is up to 11.36% greater than that of a G.I. sheet SS.	[182]
08	SS with circular and square fins in basin with CO_2 mitigation.	Hollow circular and square fin	Compared to conventional stills, square fins with wick material provide increased daily production.	[175]
09	Single sloped basin type SS integrated with extended porous fins.	Porous fin	Porous fin SS has better production in the morning than traditional still, and SS produces more distillate at shallower basin depths.	[183]
10	Optimal fin parameters used in PCM in a heat exchanger unit.	Triangular fin	By using 8 fins and a 141 mm fin length, the melting and solidification of PCM may be accelerated.	[39]

3.7.5. Using porous fins

In both summer and winter conditions, Shrivastava and Agrawal [183] discovered that adapted SS performed well while replacing the traditional SS modified with porous fins. Panchal and Sathyamurthy [186] carried out an experimental investigation with porous fins and they discovered that the distillate yield of the SS was higher with the

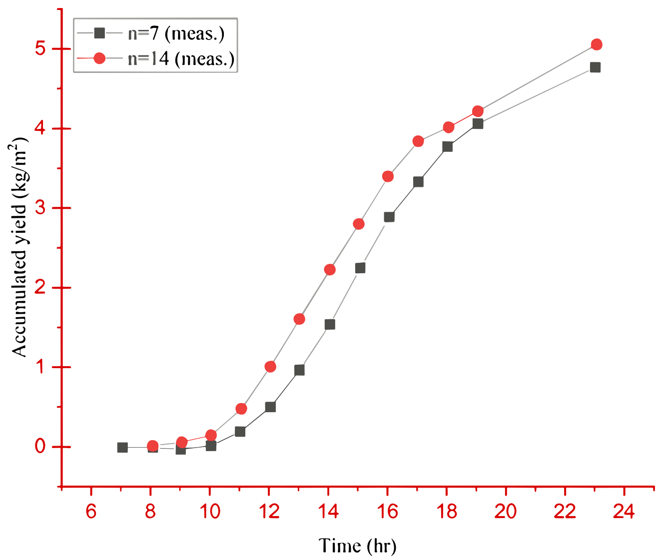

Fig. 8. Findings of distillate output with respect to fin's number [179].

porous fins than with the traditional one. Authors concluded that the porous fin supplies water in the pour holes, which is subsequently employed to create a temperature differential to produce distillate when there is no sunlight.

3.8. Using sponges

The daily output of such a still can be significantly increased by the use of sponge cubes. Kemerchou et al. [27] reported that adding sponges to SS increased production by 10% in the winter. In comparison to the baseline example, Sellamia et al. [187] found that a 0.5 cm sponge thickness raised the production yield by 57.77%, or 58%. (i.e., with no blackened sponge added). Additionally, a sponge thickness of 1.5 cm produced a yield reduction of 29.95%, or 30% (compared to the baseline scenario), while a sponge thickness of 1.0 cm only led to a yield enhancement of 23.03%. To enhance the absorber surface area for evaporation, Abu-lhijleh and Rababa'h [33] put sponge cubes over the surface of the salinized water in the basin and reported that the production went up by 18% as a result of this configuration. By employing wick, fin, and sponge, Velmurugan et al. [188] tested a single-basin SS and found that the yield increased by 15.3, 29 and 45.5% when sponge, wick, and fin were used, respectively. In addition, the impacts of black steel and coal cubes, sponge cube size, sponge volume percentage, water depth, and salinity were examined [189]. The effects of adding sponge cubes to the still, integrating a small solar pond with it, and combining the two were discussed [190]. The micro solar pond's ideal salinity level was discovered to be 80 g/kg of water. Whenever a SS is connected to a small solar pond, it is discovered to produce more energy on average per day. Moreover, performance using fins with sponges is illustrated in Fig. 9. Abdallah et al. [191] reported that sponges gather the most water throughout the day (60%).

The presence of a sponge within the solar still may impede heat transfer between the sunlight and the water, reducing the overall efficiency of the system as well as the sponge material can act as an insulator, limiting the heat absorption and transmission to the water [192].

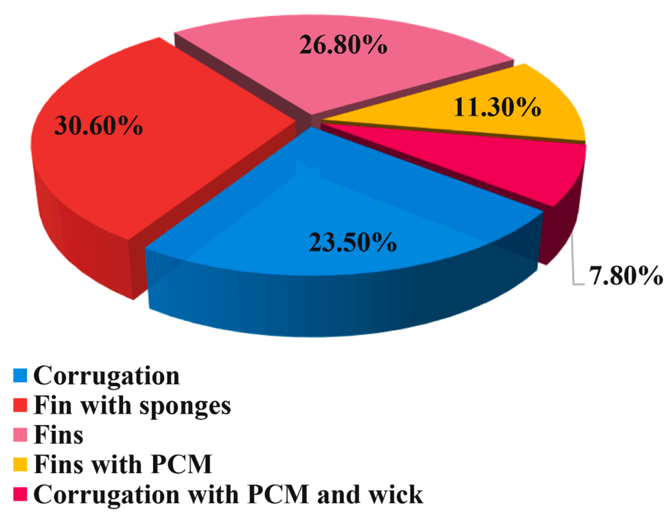

Fig. 10. Increase in performance using fin with sponges [193].

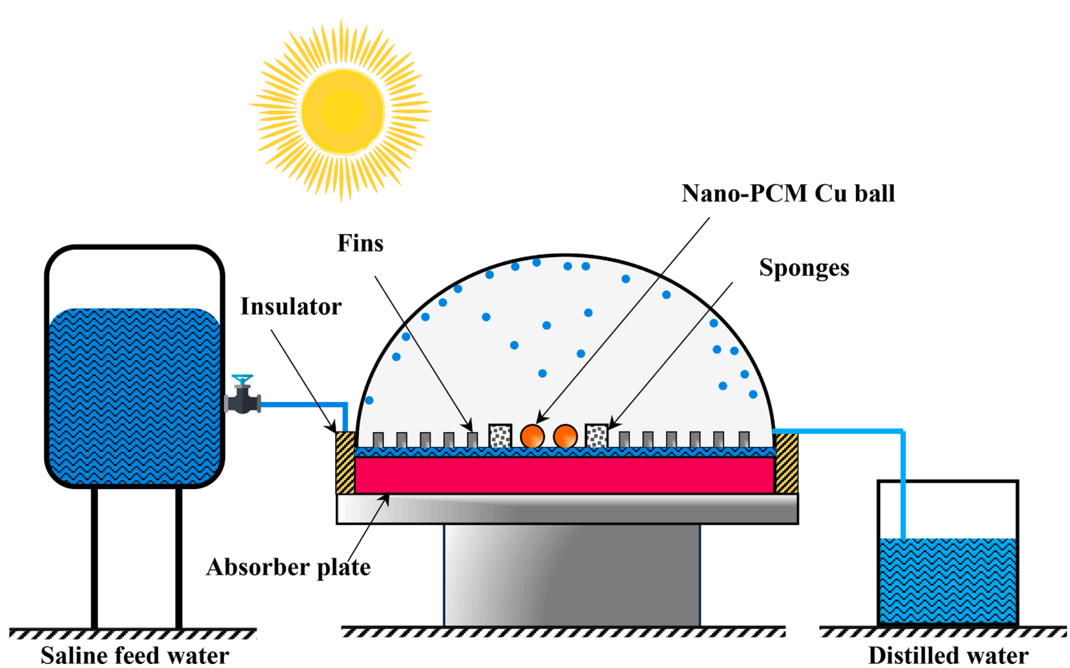

Fig. 9. Modification of solar still using sponges.

Fig. 10 highlights an improvement in performance when fins are used with sponges. In this context, research into the investigation of different types of sponges and sponge materials are worthy of future research.

3.9. Integration of PV panel and solar collector

Solar panel or collector added to a direct SS increases distillate water production and its thermal performance. Manokara et al. [48] analyzed the PV integrated SSs without insulation, with sidewall insulation, and with sidewall and bottom insulation and obtained the highest daily efficiency was 71.2% with sidewall and bottom insulation while the exergy efficiency was 4.5%. In comparison to a PV module, a PV/T collector offers greater benefits, including increased electrical and thermal yield per unit surface area. It is affordable, straightforward, and quick to repair, and it keeps PV panel cleaning expenses to a minimum even in harsher environments like deserts and coastal areas. Fig. 11 demonstrates the modification of a solar still that integrates a PV panel with thermal system.

The combined PV/T SS and active SS have been reviewed by Manokar et al. [145,194] and it is abundantly obvious from the assessment that solar and PV/T integration could still deliver up to 6–12 L/m^2/day of output. Integrating a PV panel and solar collector in a solar still system adds to the cost and complexity of the overall setup, as well as space limitations and design constraints are the major limitations of these techniques. However, simultaneously meeting electric and freshwater demand would make the system cost effective. The study related to the integration of PV module and collector is reported in Table 6 and Table 7, respectively.

3.10. Absorber plate

For absorber plates, aluminium makes the most sense due to its light weight and high heat conductivity. According to Panchal et al. [208], SSs with aluminium plates inside produce 30% more energy than SSs without aluminium plates, while SSs with galvanized iron plates inside produce 12% more energy than SSs without iron plates. Aluminium plates are therefore the finest plates to use with a SS in order to upsurge distillate output. In an experimental performance of a SS using various-sized energy-absorbing materials, for example black coal and black steel cubes, Hiljeh and Rababah [33] found that the distillate production of the SS significantly augmented from 18 to 273% when associated to a conventional SS. When compared to a traditional SS, distillate yield for SSs with Al. plate and GI plate increased by 30% and 12%, respectively. Finally, it can be found that compared to conventional SS absorbers and galvanized iron (GI) plates, aluminium plates have superior heat

Table 6
Various study of PV/T integrated SS technologies.

Serial No.	PV/T integrated solar still technologies	Yield	Reference
01	Solar panel integrated with flat plate collector	Yield 6–10 kg/m^2	[195-202]
02	PV/T integrated with evacuated collector	Yield 5.89 kg/m^2. day	[191,203,204]
03	Concentrated PV/T desalination, PV cell attached at the base of the basin	Yield 6.8 kg/m^2	[205,206]
04	SS integrated with AC-heater	Yield 5.7 kg/m^2	[207]
05	SS integrated with PV modules	Yield 4.77 kg/m^2	[207]

Table 7
Survey of SS categorization with different solar collectors.

SS categorization	Solar collectors	Year	Results	References
PV/T – HASS	PV/T collector	2008	3.5 times higher output than PSS	[193]
SBSS	Solar water heater	2012	77% higher output than the PSS	[221]
Stepped SS	Solar air heater	2013	112% output rising.	[222]
Portable asymmetrical SS	HPTM	2016	The highest and lowest values of daily output are 500 ml and 225 ml correspondingly.	[223]
Single slope single basin SS	Fresnel lens	2019	The daily efficiency and FWY developed by 84.7% and 467% correspondingly	[224]
Triple basin SS	Evacuated heat pipes	2020	The daily FWY is found 19 kg/m^2/day	[225]

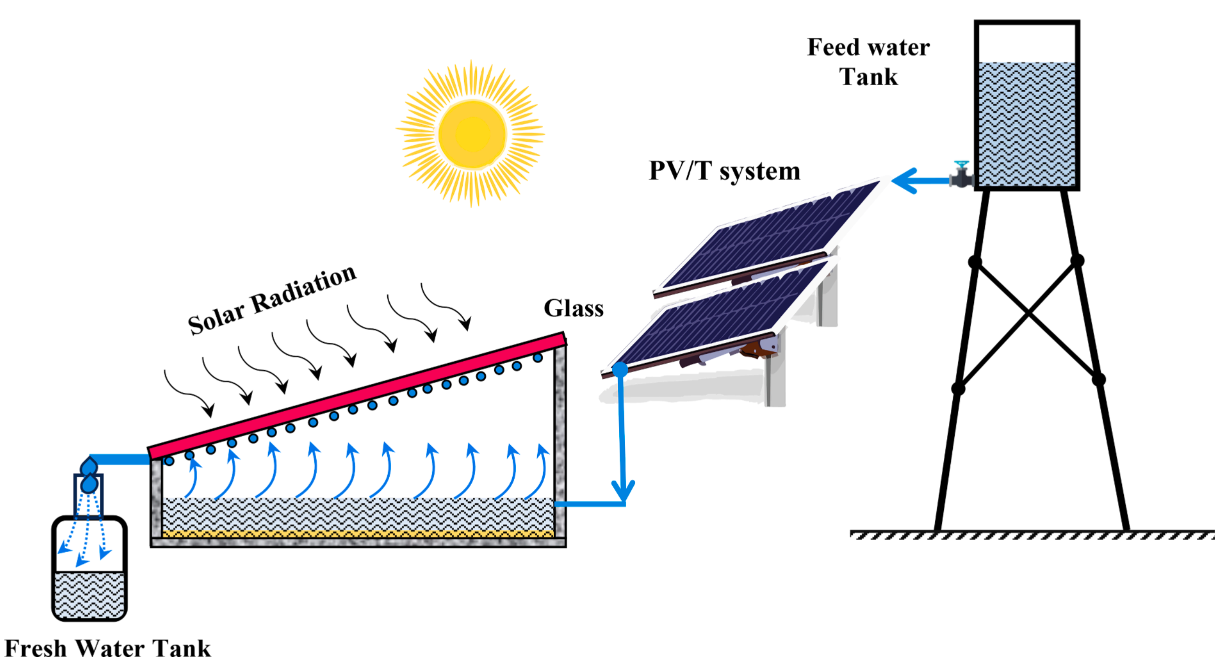

Fig. 11. Modification of solar still integrating PV-panel.

conductivity. Incorporating absorbent materials is essential for increasing still production. The effectiveness of several ways for increasing the basin absorptivity has been investigated, including the use of charcoal and the blending of violet and black dyes, which have been proven to be particularly successful in comparison to other colours for increasing the still productivity [209]. In comparison to metallic wiry sponges [210], floating absorber Al sheets [211] and the utilization of black volcanic pebbles produced higher production. The ability of these materials to stock more solar energy and improve the thermal capacity of the basin in addition to the rate of absorption in the basin. Therefore, Fig. 12 demonstrates how the growth in productivity (litres/day-area) mostly relies on the absorber that is being used. For red carnosine, this growth may be as high as 95%, while for fins and sponges, it can be as low as 7%. However, the most efficient process of adding absorber is steeped in sponges and fin which is 96% efficient. The environmental and physical conditions of each experimental trial vary, making it challenging to compare the effects of the various absorbers in this study accurately. These circumstances include the season, geographic region, style of new and utilized building materials, water temperature, brine depth, and several other site-specific elements. Black volcanic pebbles, sponges made of coated and uncoated metallic wire, and other altered absorbers were incorporated into the three stills for four studies by Abdallah et al. [210]. Numerous writers have currently described the impact of fins in their studies to increase freshwater production using different SS combinations [42,212-214]. In an experiment, Panchal et al. [215] established that coating the absorber with a nanoparticle (manganese oxide) rises the yield of SSs by 20% when compared to stand-alone SSs. Absorber plates can experience heat loss through conduction, convection, and radiation, which can reduce the overall efficiency of heat transfer to the water in the solar still. This can result in lower productivity and lower temperature differentials for effective distillation. Also, absorber plates typically have limited spectral selectivity, this limitation can lead to inefficiencies in capturing and utilizing solar energy for distillation [216]. Therefore, the determination of the size and number of absorber plates is paramount for a higher production yield.

4. Types of SS affecting the performance of direct SS

The type of SSs, such as a hemisphere SS, double slope SS, single basin SS, pyramid SS, and tubular SS, has a significant influence on its performance. Figs. 13 and 14 illustrate how the output of daily energy efficiency and yield improvement vary for various traditional SS types, both with and without modification. In Fig. 13, the daily efficiency of conventional pyramid and traditional tubular are 32% which is the highest daily energy efficiency. However, the daily energy efficiency of hemisphere SS is almost equal to that of pyramid and traditional tubular SS which is 31.90%. Additionally, the graph illustrates that the typical double slope has the lowest daily energy efficiency at 25.90%. The daily energy efficiency of the active single basin is also in the midrange.

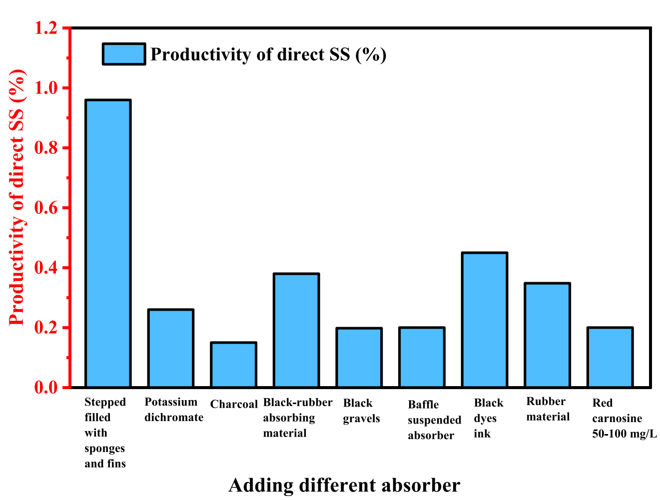

Fig. 12. Adding different absorbers to increase productivity of direct SS [217].

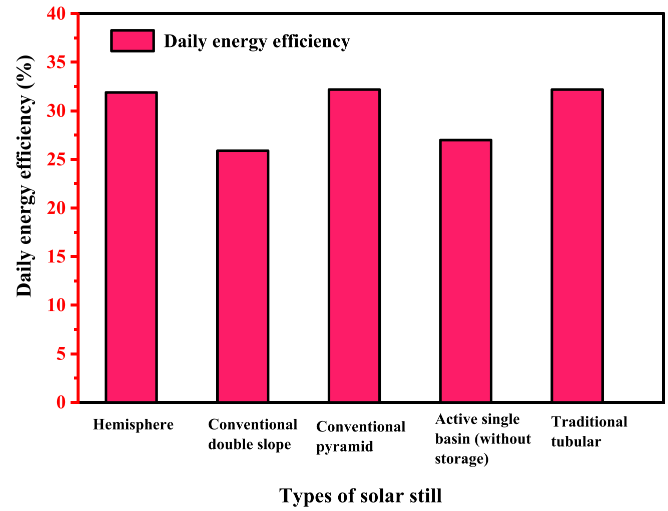

Fig. 13. Different types of SS with daily energy efficiency [2,40,44,153,218].

Moreover, in Fig. 14, different types of SS with modifications represent different outputs of yield improvement. Consequently, the yield improvement of pyramid SS with hollow circular fins and PCM shows the highest rate, which is 101.5%. In the other case, the hemisphere with 4 cans of paraffin wax shows a yield improvement of 92.80%. Modification with hollow circular fins and PCM shows the best response of the output rate of yield improvement. For this reason, different types of SS are vital to the growth of the output of fresh water. Angappan et al. [219] revealed that the daily production of the active solar still (ASS) and passive solar still (PSS) was 5.5 L/m^2 and 3.9 L/m^2, respectively. Moreover, the adjustment increased freshwater output by almost 41% as compared to the PSS. Additionally, the PSS and ASS had costs per liter of around 0.0101 and 0.0091, respectively. Furthermore, compared to PSS, ASS decreased CO_2 emissions by 41%. The cumulative productivity of the solar still employing conch shells as an energy storage biomaterial and porous medium was 10.8% higher than that of the conventional sun still (CSS), according to Dhivagar et al. [220]. Furthermore, the CSSS beat CSS by 10.3% and 9%, respectively, in terms of energy and energy efficiency.

5. Conclusions

Several parameters are explored in this research with the intention of enhancing SS production. The primary goals of this study are to enhance yields, performance rates, and freshwater productivity output. The study's key conclusions are as follows:

- For a single-slope SS, nanoparticle-mixed PCM (paraffin wax) increases production output by 73.8%, whereas the tubular SS with pure PCM (paraffin wax) and black wick enhances performance by 82.16%. A single-slope, single-basin SS with stearic acid-based PCM enhances daily productivity by 80.12%. Results indicate that the daily output of a copper ball loaded with PCM is 4460 ml/m^2/day and that of a copper ball without PCM is 3520 ml/m^2/day. Importantly, SS and storage tanks work together to create more distilled water.
- Different nanoparticles such as Al_2O_3, ZnO, CuO, SiC, GO, Fe_3O_4, and TiO_2 have been used in the SSs to enhance their productivity. Integrating nanoparticles and carbon nanotubes results in an increasing

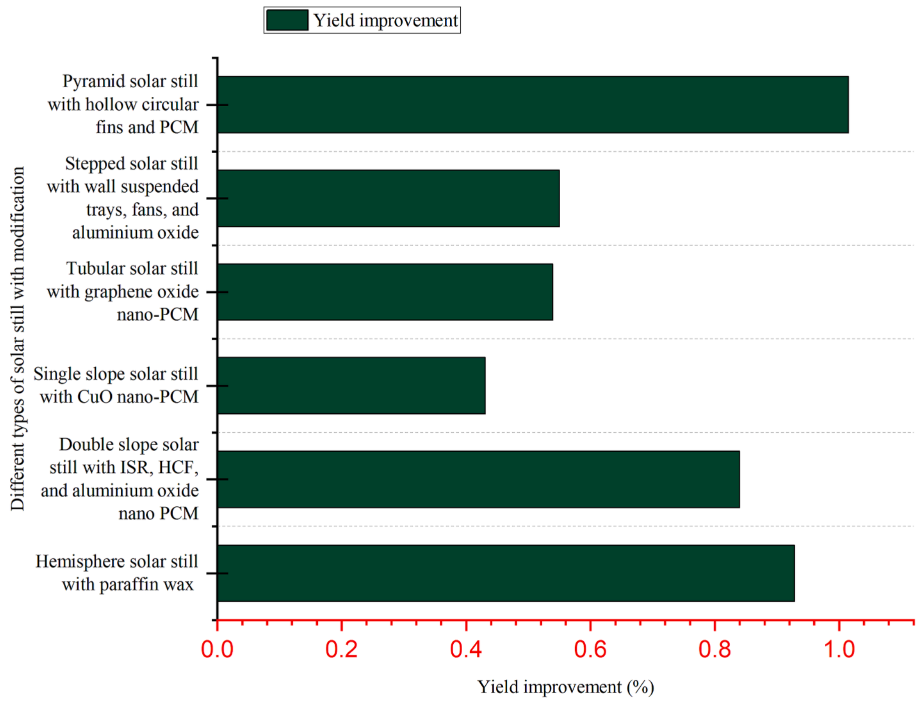

Fig. 14. Yield improvement VS different types of SS with modification [2].

temperature difference between the water and the glass surface, thus enhancing productive yield. Among the different nanoparticles, CuO has the highest thermal conductivity. Additionally, hybrid nanoparticles increase the yield of fresh water in SSs.

- Reflectors also increase freshwater generation by an average of 21% yearly. Black sand, meanwhile, continues to boost water production by 14%, and after applying a fin, the production further rises by 16%. Remarkably, sponges also contribute 10% of productivity gains. The output rate and efficiency also increase with the addition of PV panels. Further, using aluminium plates as absorber plates boosts output by around 30%.
- The climatic and operational parameters such as solar intensity, wind velocity, relative humidity, and feed water temperature affect the freshwater production of the SSs. A modest rise in ambient temperature also speeds up production. However, the freshwater output increases once the wind speed is below 4.5 m/s.
- Furthermore, different SS models and modifications exhibit a range in performance output and yield improvement. A crucial aspect that increases production is the addition of absorber. Results suggest that the productivity of direct SS will improve by about 96% with the addition of absorbers. In this analysis, it is recommended that the parameters and various methodologies be used in combination rather than separately to boost the production rate.
- Finally, fins, PCM, hybrid nanoparticles, Al absorber plates, and sponges are the suggested parameters and approaches. When these components are used together, they will improve yield while also boosting the production rate of fresh drinking water more than they are used individually.

6. Future works

Different performance enhancement techniques have been applied to enhance the production yield of solar desalination system in numerous research works. However, there are several areas where still needs further attention to work on as follows:

- Hybrid nanoparticles included in copper balls with the PCM warrant further study to improve surface area and quicken heat transfer rate.
- Additionally, black sand is implemented in the SS as a sensible heat storage material and has various fin features that aid in the PCM's better melting and solidification. The design parameters, such as the sizing and configurations of fins, reflectors, absorber plates, etc., can be optimised using intelligent techniques.
- Sponge usage is additionally promoted to boost output rates. Moreover, hybrid nanoparticles may be used to increase energy and exergy efficiency in solar stills most significantly.
- Further research is necessary considering the filtration of produced water from SS and purifying water for human consumption and safety. Design modifications of SS are made in such a way that fouling factors due to salt deposition won't have a decreasing effect on its efficiency.
- Determination of optimal mixing ratio of different nanoparticles for the preparation of hybrid nanoparticles is warranted further investigation.
- Research work can be done based on the nanoparticles' erosion, complexity, corrosion, and extendable duration. Additionally, characterizing nano-fluids, ensuring their stability, and reducing pressure drop in direct SS should also be promoted.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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