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Effect of various factors and diverse approaches to enhance the performance of solar stills: a comprehensive review

Laxmikant D. Jathar[1,2] · S. Ganesan[1] · Kiran Shahapurkar[3] · Manzoore Elahi M. Soudagar[4] · M. A. Mujtaba[5] · Ali E. Anqi[6] · Muhammad Farooq[7] · Abdulqhadar Khidmatgar[8] · Marjan Goodarzi[9,10] · Mohammad Reza Safaei[11]

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Abstract

The need for fresh drinking water is increasing rapidly, and drinking water availability reduces day by day. Solar desalination is a viable option to change saltwater to fresh drinkable water. Solar still used for desalination includes processes like heating, evaporation, and condensation. The major problem faced by solar stills is that they have low productivity. Therefore, high demand for freshwater cannot be met. The present review aims to provide the researchers with an idea to select suitable methods for enhancing solar stills' performance. This article mainly focuses on the climatic, design, and operational parameters affecting the performance of solar stills. Results reveal that a combination of the incredible intensity of solar radiations, solar still type, and regions with optimum temperature can provide higher daily distillate output. Further, high productivity can be achieved with inclined solar stills by making an inclination angle equivalent to the location's latitude. A water depth of around 1 cm can provide the best output in terms of productivity for conventional solar stills. A combination of V-corrugated absorber plate with fins and energy storing materials coupled with external reflector plates can provide optimized conditions to enhance productivity. The performance of solar still can be improved by minimizing the gap between absorber plates and condensing cover. Finally, the sun tracking system, either single or dual axis in solar still, can enhance productivity.

Keywords Desalination · Solar still · Solar radiations · Phase change materials

✉ Marjan Goodarzi
mgoodarzi@lamar.edu

1 Department of Mechanical Engineering, Vel Tech Rangarajan and Dr. Sagunthala R & D Institute of Science and Technology, Chennai, Tamil Nadu 600062, India

2 Department of Mechanical Engineering, Imperial College of Engineering and Research, Pune, Maharashtra 412207, India

3 Centre of Excellence for Advanced Manufacturing Engineering, School of Mechanical, Chemical and Materials Engineering, Adama Science and Technology University, 1888 Adama, Ethiopia

4 Department of Mechanical Engineering, Glocal University, Delhi-Yamunotri Marg, SH-57, Mirzapur Pole, Saharanpur District, Uttar Pradesh 247121, India

5 Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

6 Department of Mechanical Engineering, College of Engineering, King Khalid University, Abha 61421, Saudi Arabia

7 Research Centre for Carbon Solutions, IMPEE, Heriot-Watt University, Edinburgh EH14 4AS, UK

8 Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia

9 Department of Mathematics, Faculty of Science, King Abdulaziz University, P.O. Box 80259, Jeddah, Saudi Arabia

10 Department of Medical Research, China Medical University Hospital, China Medical University, Taichung, Taiwan

11 Department of Civil and Environmental Engineering, Florida International University, Miami, FL 33174, USA

Introduction

The presence of quality drinking water strongly influences the socio-economic development of a country. Near about 97% of water present on the earth is saline water [1]. This saline water can neither be used for industrial, agricultural, nor for drinking purposes. Presently the need of the hour is to convert saltwater into clean, usable water. To achieve this, the desalination process is the best alternative that includes heating, evaporation, and condensation processes. The best device available for the desalination process is solar still [2]. People around the globe are facing the problem of clean and potable water. Therefore, solar still can be considered as the best alternative that is cheap and possess low maintenance [3, 4]. However, low productivity concomitant with solar stills is hindering the distillate output per day [5]. Thereby, a comprehensive study involving different aspects that affect the output of solar still needs to be reviewed.

Furthermore, using renewable energy sources for power generation and heating/cooling purposes is an attractive idea [6]. As renewable energy is considered as green and clean energy [7], the different factors affecting solar still efficiency are categorized as climatic, operational, and design. Table 1 depicts the details of various factors affecting the performance of solar still. Out of these, the climatic factors are considered metrological factors that are not controlled by human beings. Therefore, it is necessary to concentrate on the operational and design aspects of solar stills for improving their overall performance [8, 9].

In the recent decade, due to global warming, a temperature rise is observed worldwide. Acute shortage of potable drinking water is reported due to a decrease in sources of ground-level water. Therefore, much attention is given to harnessing conventional and non-conventional resources. Solar energy is recognized as one of the cleanest energy sources utilized for power generation and other uses [3]. Solar still, in particular, has emerged as one of the best alternatives for generating potable water from saline water. The process of removing salt content from saline water and converting it into potable drinking water is known as desalination [10]. Seawater contains about 55% chlorine ions, 30.7% sodium ion, 7.7% sulfate ions, 3.6% magnesium ion, 1.2% calcium ions, and 1.1% potassium ions of dissolved matters that vary from place to place. The desalination process works on two methods, namely thermal and electrical desalination. The thermal desalination process utilizes solar energy or sun radiation [11, 12]. Solar radiations are used to heat the saline water resulting in evaporation of the saline water. Vapors formed owing to evaporation are collected on the condensing surface, and condensation of these vapors results in water droplets [13, 14].

On the other hand, there are several membranes and thermal processes like reverse osmosis (RO), multi-effect desalination (MED), multistage flashing (MSF), adsorption desorption desalination (ADD) and ion exchange (IEX) [15, 16]. However, high energy consumption and brine disposal problem are associated with these technologies. Figure 1 depicts the energy consumption from various desalination technologies. The most leading desalination technology by considering volume is RO with a portion of 65%, followed by MSF, MED, ED, and others with a portion of 21%, 7%, 3%, and 4%, respectively [17, 18]. Figure 2 represents the amount of water produced from different technologies.

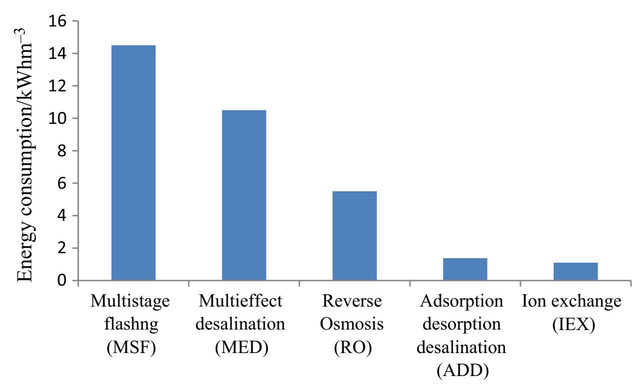

Fig. 1 Energy consumption from different technologies [15] (adapted with permission from ELSEV. B.V. with LIC. No. 5030650070249)

Table 1 Various parameters affecting the performance of solar still

Climatic parameters	Design parameters	Operational parameters
The intensity of solar radiation	Selection of material	Salinity of water
Wind speed	Depth of water	The flow rate of water
Ambient temperature	Absorber plate area	Use of dyes
Dust and cloud cover	Thermal energy storage materials	Others
Latitude and longitude of the location	The inclination of the cover plate	
	The thickness of the cover plate	
	Use of internal/external reflectors	
	Gap distance	
	Sun tracking system	
	The thickness of insulation and insulating material	

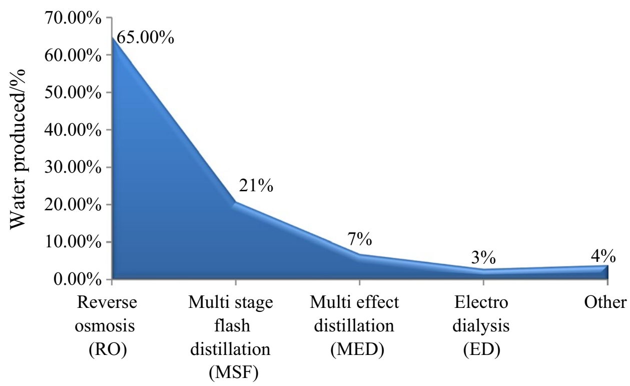

Fig. 2 Amount of water produced from different technologies [17] (adapted with permission from ELSEV. B.V. with LIC. No. 5030640738937)

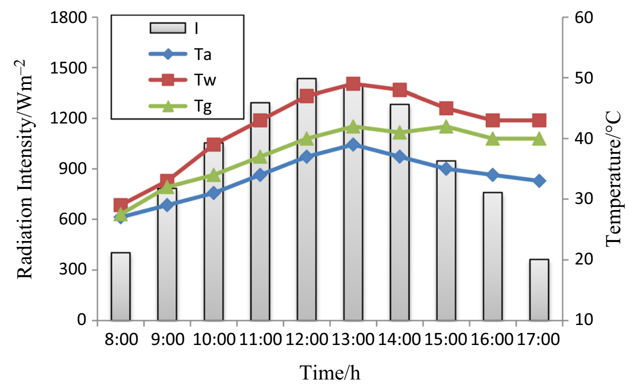

Fig. 3 Variation in radiation intensity from morning to evening [13] (adapted with permission from Taylor & Francis with LIC. No. 5030750006189)

Malaiyappan and Elumalai [19] studied single-basin solar still by using glass, plastic, and aluminum as a basin material. Results show that aluminum material gives better performance than other materials, and the productivity of solar still depends upon the thermal conductivity of a material. Sameet al. [20] examined single-basin solar still performance in an arid region of Pakistan. The experiment conducted for eight days revealed an output of 1.7 L day^{-1}. Gnanadasonet et al. [21] worked on single-basin solar still to enhance efficiency. Two similar-sized solar stills were fabricated for the experiments. The first still was tested experimentally at atmospheric pressure, while various modifications (use of fins, pebbles, coating of a basin with black paint) were done to test the second. Results show that modified solar still provides better performance as compared to the one without modification. Abujazaret et al. [22] designed an inclined stepped solar still to conduct experiments in Malaysia's Bangi region. The experimental setup comprised 28 trays with dimensions of 0.6 m height and 1.2 m length to enhance the evaporation rate. Results revealed productivity of 4.383 L m^{-2} day^{-1}. Rashidi et al. [23] numerically studied nanoparticles' effect on the productivity of stepped solar still. Results show that increasing the concentration of nanoparticles from 0 to 5% enhanced the productivity of stepped solar still by 22%. Most of the research is performed on conventional solar stills but owing to their low productivity. These stills are not utilized in day-to-day life regularly.

Based on the current work, it is noted that a comprehensive assessment that affects the solar still performance based on climatic, design, and operational parameters is lacking. In the present work, a review of solar stills is carried out addressing the following points: (a) climatic conditions (intensity of radiation, ambient temperature, wind speed and latitude and longitude of location), (b) design parameters (selection of material, depth of water, absorber plate area, thermal energy storage materials, the thickness of insulation and insulating material, the inclination of the cover plate, cover plate thickness, use of internal/external reflectors, gap distance, sun-tracking system), and (c) operational parameters (salinity of water, the flow rate of water, use of dyes).

Parameters affecting the productivity of solar still

Climatic parameters

Various climatic parameters that affect the productivity of solar still are listed below.

- The intensity of solar radiation
- Wind speed
- Ambient temperature
- Dust and cloud cover
- Latitude and longitude of the location

Intensity of solar radiation

Distillate output associated with solar still is strongly affected by the intensity of solar radiations. The higher the intensity of radiations, the better will be productivity [18, 24]. Hourly variation in atmospheric temperature (T_a), water temperature (T_w), glass temperature (T_g), and intensity of radiation is depicted in Fig. 3. It is observed that temperature rises from 8:00 to 14:00 and then starts to decline due to the low intensity of radiations. In the afternoon session between 12:00 and 13:00, the intensity of radiation and ambient temperature is at the higher side worldwide. The temperature of water and glass shows an increasing trend toward radiation intensity, enhancing the productivity in the afternoon session.

Moreover, maximum water and glass temperature are found in afternoon session; hence, productivity get increased [13]. The effect of solar intensity on the thermal output of single-slope solar still was investigated by Omar et al. [25]. Experimental results conclude that solar still output is directly relative to the concentration of solar radiations. Maximum productivity is obtained in the afternoon, attributing to higher intensity of radiation. Evaporative cooling system integrated with single-slope solar still was analyzed by Almuhanna [26]. Results revealed the intensity of solar radiations dictates the solar still productivity. It is further reported that 5.9 L m^{-2} is the distillate output achieved from the tests. Nafey et al. [27] studied various parameters that can affect the solar still performance and concluded that at a high degree of temperature, solar still can give better performance. Ghoneyemet al. [28] analyzed solar still and established empirical equations to express the dependency of solar still productivity on ambient temperature and solar radiation. A literature survey based on the location and intensity of radiation is depicted in Table 2.

Based on the above literature, it can be concluded that a combination of the incredible intensity of solar radiations and regions with high temperatures can provide better productivity in terms of daily distillate output. However, the solar still utilized for generating distillate output can significantly affect productivity. Single-basin multi-step solar basin (1100 W m^{-2} and 8.9 L m^{-2} day^{-1}) and multi-wick solar still (1198 W m^{-2}and 9.012 Lm^{-2}) provide better productivity as compared to triangular prism solar still (1256 W m^{-2}and 0.91 L m^{-2}).

Wind speed

Another significant factor influencing the productivity of solar stills is wind speed. Sebaii [29] evaluated the effect of wind speed on active and passive-type solar stills experimentally. Additionally, numerical calculations have also been computed. Results infer that solar still productivity is directly relative to the wind speed. Soliman [30], Garg and Mann [31] also predicted that productivity enhances higher wind speed and solar radiations. Tiwari et al. [32] studied the parameters affecting active and passive distillation. Results inferred that the distillate output of solar still increases with increasing wind velocity up to a certain peak point. Productivity remains constant after attaining peak point. Zurigat et al. [33] worked on a regenerative solar desalination unit and concluded that wind velocity has a substantial effect on the productivity of solar still. Productivity can be enhanced by increasing the wind velocity from 0 to 10 m s^{-1} to about 50%, depicted in Fig. 4. Reddy et al. [34] carried out a thermal analysis on basin type of solar still and invented a correlation model

Table 2 Performance of solar stills at different locations and intensity of radiation

References	Design of solar still	Location	The intensity of the radiation/Wm^{-2}	Remark
[146]	Passive solar still	Egypt	978.52	Average productivity was 4.1 L m^{-2}
[147]	Triangular pyramid solar still	Chennai, India	984.73	Latent heat of thermal energy storage system integrated with solar still produced 4.5 L m^{2} day^{-1}
[148]	Hemispherical solar still	Tamil Nadu, India	732 and 745	Results show that distillate output can be increased by lowering the cover temperature
[149]	Single-basin solar still	Mashhad, Iran	943.5	The productivity of the still can be improved by introducing partitions in the still
[150]	Single-basin multi-step solar still	Selangor, Malaysia	1100	The modification resulted in increased productivity of solar still from 6.9 to 8.9 L m^{-2} day^{-1}
[151]	Basin solar still	Guwahati, India	919	Maximum distillate per day was reported to be around 3.94 L m^{-2}
[50]	Hybrid solar still	Tamilnadu, India	1039	Inclined still combined with fin-shaped absorber gives 5.21 L m^{-2} distillate output
[152]	Triangular prism solar still	Victoria, Australia	1256	Triangular prism solar still produced an output of 0.9 L m^{-2} day^{-1}
[153]	Floating wick, multiple effect diffusion solar still	Patiala, India	917	Basin with wick material and heat exchanger were used for waste heat recovery. Results depict enhanced productivity
[154]	Weir-type cascade solar stills	Zahedan, Iran	817	Results show that phase change materials with a weir type of cascade solar still can give better distillate output
[155]	Multi-wick solar still	Allahabad, India	1198	The maximum yield obtained is 9.012 L day^{-1} by using a black cotton wick

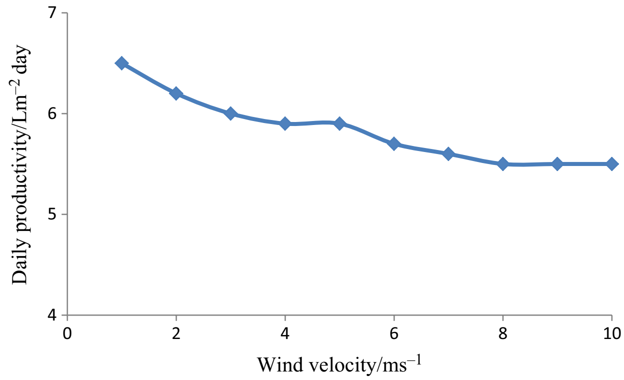

Fig. 4 Effect of wind speed on the productivity of solar still [27] (adapted with permission from ELSEV. B.V. with LIC. No.4827130278404)

on the effect of wind speed on radiative, convective, and evaporative heat transfer coefficient. The active and passive solar still critical or typical speeds were 10 and 8 m s^{-1} for summer and winter seasons. However, there is sufficient literature available based on the wind speed effect influencing productivity. Research on the optimum values of wind speed that can increase the overall production is lacking.

Dust and cloud cover

Accumulation of dust and dirt particles on the solar still glass surface can reduce solar energy conduction and reduce productivity. Hegazy [35] studied the influence of dust particles on the solar still output in Egypt's Central regions. Experiments were conducted for one month without cleaning the glass cover. Results revealed that the presence of dust and dirt particles reduced the productivity of solar still significantly. Accumulation of dust on evacuated tube collectors was examined by Nasharet al. [36]. For the experiments, two collector blocks, one with dust and dirt particles and the other in cleaned condition, were used. Results show that the dusty collector block's heat was 60–70% lower than the clean collector. Nashar [37] investigated the seasonal effect of deposition of dust on the evacuated tube collector. The experimentation was carried out in Abu Dhabi, United Arab Emirates. Results inferred that dust deposition could drop the glass transmittance by 10 to 18%. Zamfiret et al. [38] studied the influence of cloud cover on flat plate solar collectors' efficiency. Results indicated that cloudy conditions dictate the output from solar collectors. Most of the investigations carried out in dusty environments reveal that productivity reduces with such natural occurrences, and subtle precautions can enhance productivity.

Table 3 The productivity of solar still at different latitude and longitude

References	Location	Latitude and longitude	Productivity/ Lm^{-2} day^{-1}
[156]	Jeddah, Saudi Arabia	21.543° N 39.172° E	4.90
[157]	Ahmedabad, India	23.030° N 72.580° E	3.80
[158]	Mashhad, Iran	36.300° N 59.600° E	3.14
[159]	Tipaza, Algeria	28.000° N 2.0000° E	4.00
[160]	Tamil Nadu, India	13.090° N 80.270° E	2.90
[161]	Adrar, Algeria	27.866° N 0.2833° E	1.31
[162]	Delhi, India	28.613° N 77.209° E	7.50
[43]	Amman, Jordan	31.949° N 35.932° E	5.68
[163]	Tanta, Egypt	30.783° N 31.000° E	5.70
[164]	Isa Town, Bahrain	26.173° N 50.547° E	5.90
[165]	Tamil Nadu, India	13.090° N 80.270° E	4.00
[166]	Dhahran, Saudi Arabia	26.266° N 50.150° E	5.71
[167]	Rajasthan, India	26.572° N 73.839° E	3.90
[168]	New Delhi, India	28.613° N 77.209° E	2.50
[169]	Selangor, Malaysia	3.333° N 101.500° E	5.00
[170]	Muscat, Oman	23.610° N 58.540° E	6.00
[171]	Valencia, Spain	39.466° N 0.3833° W	1.60
[172]	Allahabad, India	25.450° N 81.850° E	2.00
[173]	Foggia, Italy	41.464° N 15.546° E	1.80
[174]	Yokohama, Japan	35.444° N 139.638° E	9.44

Latitude and longitude of the location

The experimental setup's latitude and longitudinal location plays a pivotal role in determining the overall productivity of the solar stills [39]. Researches carried out with these parameters at different locations worldwide are presented in a tabular form in Table 3. This information is utilized to build up a variation pattern among the optimum cover tilt angle and latitude of the location. Longitude and latitude are imaginary lines that run across the earth. Longitudes are vertical lines that meet at the North and South poles, whereas latitudes are horizontal lines running from East to West. Experimental results inferred that latitude coordinate location influences the productivity than coordinates of longitude [40]. Further, it also noted that productivity is maximum with inclined solar stills when the inclination angle is made equivalent to that location's latitude.

Design parameters

Various design parameters affecting the solar still productivity are listed below:

- Selection of material
- Depth of water
- Absorber plate area
- Thermal energy storage materials
- The inclination of the cover plate
- Cover plate thickness
- Use of internal and external reflectors
- Gap distance
- Sun tracking system
- The thickness of insulation and insulating material

Selection of material

Evaluating the properties (thermal conductivity, absorptivity and transmissivity) of still material is the first step in the fabrication of solar stills, since the selection of materials for the various components of solar still plays a vital role. Researchers have investigated the various materials for basin and cover plate of solar stills. Burbano [41] studied the efficiency of solar still by using different basin materials. In the study, stainless steel and aluminum were utilized as basin materials. Results showed that aluminum could give better results than stainless steel due to its good thermal conductivity. Alaudeen et al. [42] analyzed the solar stills by considering glass as basin material. Solar still with basin size of $1 \times 1 \times 0.2$ m^3 was tested with various heat-storing materials. Tests infer a considerable enhancement in the solar still output by incorporating corrugated sheets as the basin material. Badran et al. [43] performed experiments on a single-slope, solar still using an asphalt basin liner. Test results revealed that the productivity enhanced by around 51% by using an asphalt basin liner. Ghoneyem et al. [28] designed and fabricated basin solar still with different cover plate materials (glass and plastic). Experimental results inferred that the glass cover plate with the minimum thickness (3 mm) substantially influences the solar still distillate output. Apart from the investigations above, cast iron has also been used as basin material. However, rusting and corrosion of cast iron have restricted the utilization of solar stills. Therefore, based on the literature, it can conclude that aluminum and glass with nominal thickness can be used as basin and cover plate material, respectively, for better output.

Depth of water

The depth of water in the solar still is one of the significant design factors that must be assessed to enhance the overall distillate output from stills. The productivity of solar still is maximum at a minimum depth of water. Figure 5a and b shows the effect of water depth on the efficiency and annual yield of solar still. Retaining the minimum depth of water in solar still is a challenging task. To achieve this, various augmentation techniques have been put forth by many researchers. The details of the results attained for water depth and solar still type are mentioned in Table 4.

From the above literature, it is observed that the depth of water influences productivity inversely. Maintaining a minimum water depth is a difficult and challenging task due to the evaporation of water droplets continuously. It is also reported that wet clothes are used to maintain water's required depth in the solar stills. However, it is concluded that the water depth of around 1 cm in the basin can give the best output in terms of productivity in the case of

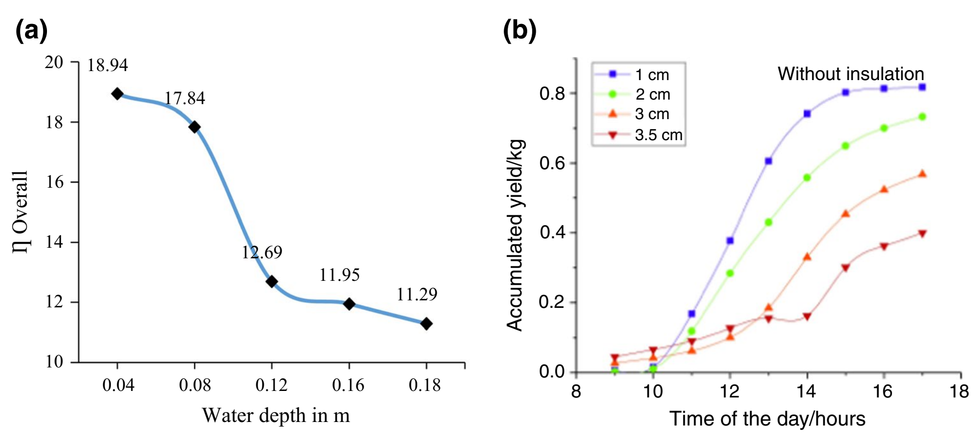

Fig. 5 Effect of water depth on the (**a**) efficiency and (**b**) annual yield of solar still [143] (adapted with permission from ELSEV.B.V. with LIC. No. 4827130436034 and 4827130628421)

Table 4 Review based on the depth of water and different solar stills

References	Type of solar still	Depth of water/cm	Modifications	Remarks
[175]	Basin type	1, 4, 6, 8 and 10	Five different brine depths were considered	Results show that a decreasing trend of productivity was associated with increasing depth of the brine
[176]	Single slope	2, 4, 6 and 8	Transient analysis of solar still	Results show that productivity decreases with the depth of water for saline water temperature (≤ 40 °C)
[177]	Passive and active solar still	5, 10 and 15	The concept of the solar fraction is used	Results show that a considerable drop in the convective heat transfer coefficient is observed by increasing water depth. This is attributed to the solar fraction that plays a vital part at low angles of altitude
[27]	Single slope	2, 4, 6, and 7	Four different solar stills were designed and fabricated	Productivity decreases by around 14% by increasing the water depth to 7 cm from 2 cm
[178]	Single and double slope	1.5, 3, and 4	Mirrors on the internal surface of solar still were used for better reflectivity	Solar still distillate output reduces with an increase in water depth
[179]	Passive solar still	4, 8, 12, 16, and 18	Five different brine depths were considered	The result shows that the heat transfer coefficient depends on the water depth of solar still, and production is inversely related to the water depth
[180]	Pyramid solar still	1, 2, 3, and 3.5	Nanoparticles of TiO_2 mixed with black paint were used to enhance the heat-storing capability	12% increase in productivity is attained with 1 cm depth of water as compared to 3.5 cm
[181]	Single basin	2, 4, 8, and 16	Water surface and cover distance of solar still were varied with a change in depth of water	Results revealed that by varying water surface and cover distance from 9 to 23 cm, overall output increased by around 26%
[182]	Single- and double-basin dual slope	1, 2, 3, 4, and 5	Glass is used as basin material	Maintaining 1 cm depth of water assists in attaining a distillate output of 4.315 L m^{-2}
[183]	Single-basin dual-slope still	1, 3, 5, 7, 9, 10, 11, 13, 15, and 17	Passive and active solar still	Experimental results reveal that 1 cm depth of water gives the highest annual yield. Water temperature of glass cover and water and distillate output are the functions of climatic parameters
[55]	Single-basin dual-slope still	1, 2, and 3	Circular hollow and square hollow fins	Distillate output was maximum at 1 cm depth of water using circular fins
[143]	Pyramid solar still	1, 2, 3, and 3.5	Acrylic material was used for fabrication	The highest distillate output 3.27 L m^{-2}, was achieved at a minimum depth (1 cm) of water. Results of the experiments are in (Fig. 5b)

conventional (single basin) solar still. Using high water depth, the amount of water existing in the basin will be more due to which time required for heating the water and evaporation.

In contrast, at shallow water depths like 2 to 5 mm, the basin's water is significantly less. It may not be uniformly distributed over the steps because of dry spots due to rapid evaporation. In such conditions, though the depth of water is less, the productivity of the still may decrease; hence, it is essential to have an optimum depth of water that will enhance the still's productivity [44, 45].

Absorber plate area

The absorber plate is mainly used to absorb maximum solar radiation; thereby, the absorber plate's area plays a vibrant role in designing solar still [46]. Copper, aluminum, steel are most widely used as materials for absorber plate [47]. Many researchers have proved that the performance of a solar still improves by enhancing the surface area of evaporation [48]. Numerous augmentation techniques to increase surface area are formulated by many investigators. Velmurugan et al. [49] developed a galvanized iron absorber plate with 25 trays. Fins and sponges were also incorporated to enhance the exposed surface area. Results show that productivity improved by the incorporation of fins and sponges on the absorber plate. Hansen and Murugvel [50] performed experiments by considering different absorber configurations. The integrated solar still was tested with different geometries of absorbers, namely flat grooved and fin-shaped. Results reveal that fin-type absorber yields higher productivity (25.7% higher than flat absorber). Figure 6 depicts the variation in overall efficiency with different types of the absorber.

Performance of inclined solar still with absorber plate possessing rectangular grooves and ridges was studied by Anburaj et al. [51]. Tests reveal yield of solar still was

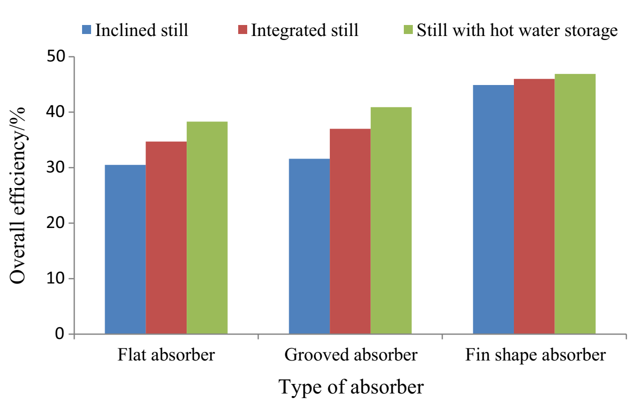

Fig. 6 Variation in efficiency with type of absorber [50] (adapted with permission from ELSEV.B.V with LIC. No. 4827130774445)

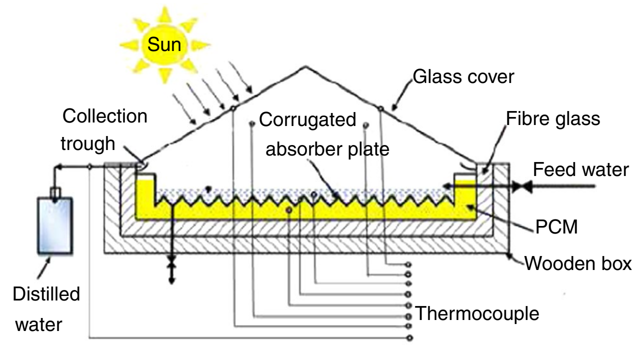

Fig. 7 Still with V-grooved absorber plate [52] (adapted with permission from ELSEV. B.V. with LIC. No. 4827041335546)

around 4.27 Ld ay^{-1} owing to the excessive heat absorbed in energy storage materials placed in rectangular grooves. Kabeel et al. [52] investigated pyramid solar still having V-grooved absorber plate with phase change material depicted in Fig. 7. Results show that an 87% increase in distillate output as compared to conventional pyramid solar still was observed. Elshamy et al. [53] studied tubular solar still using a flat plate and semicircular corrugated absorber shape. Figure 8 shows a semicircular corrugated absorber. Experimental results showed that the semicircular absorber plate gave 4.3 L m^{-2} distillate output (26.46% higher than the flat plate absorber). Deu [54] worked on a non-continuous absorber area and determined the thermal efficiency and overall thermal losses of semispherical solar collector. Effect of hollow circular and hollow square fins on the surface of the mild steel absorber plate was investigated by Jani and Modi [55]. For the experiments, circular fins and square

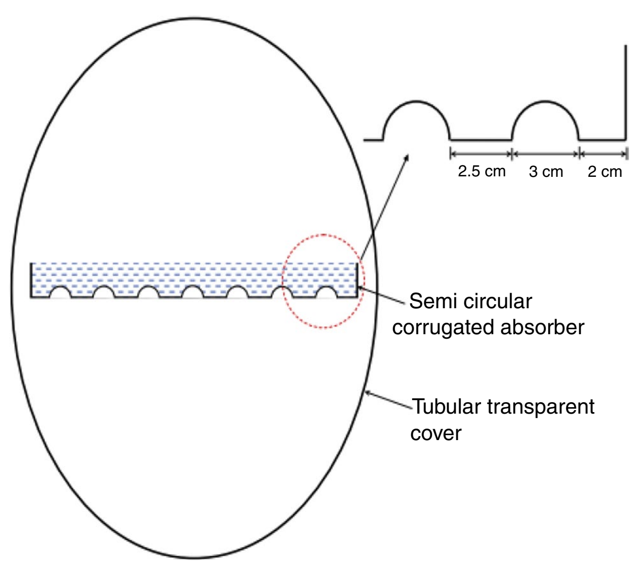

Fig. 8 Semicircular absorber plate [53] (adapted with permission from ELSEV.B.V. with LIC. No. 4827130949744)

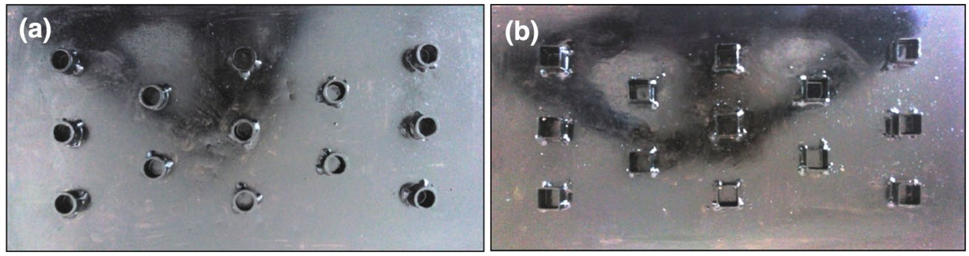

Fig. 9 **a** Hollow circular and (**b**) square fins [55] (adapted with permission from ELSEV.B.V. with LIC. No. 4827060084558 and 4827060273211)

plate fins (Fig. 9a and b) made up of mild steel with dimensions of 25 × 20 × 2 mm were used. Experimental results showed that absorber plates with hollow circular fins gave more distillate output than hollow square fins. The productivity of any solar still is strongly influenced by the evaporative area. Integration of fins in a basin of solar still increases the surface area and enhances the rate of evaporation, leading to improving the productivity of solar still [56]. Sathyamurthy et al. [57] studied the influence of fin on an absorber plate of tubular solar still. The result of experimentation shows improvement in surface area and evaporation rate that leads to accelerating the productivity of still. Panchal et al.[58] assessed the impact of vertical and inclined fin and compared the results with CSS. The results show that 27 and 25% increment in the productivity of still is obtained with inclined and vertical fins compared to CSS. Finally, it can be concluded that a combination of V-corrugated absorber plate with fins and energy-storing materials can provide optimized conditions to enhance productivity.

Use of thermal energy storage materials

Enhancing the productivity of solar still necessitates the temperature of basin water to be high [59]. Various augmentation techniques are employed to achieve temperature rises, such as thermal energy-absorbing and storing materials, the use of phase change materials, and the use of nanoparticles [39, 60]. A nanofluid is a substance that contains nanosized particles [61]. Sun-oriented thermal advancements utilize the whole solar spectrum to give high temperature [62]. Figure 10 shows various thermal energy storage materials. Incorporating materials that are energy absorbent has a very prominent role in the fabrication of solar stills [63]. A substantial amount of work is reported on the usage of energy-storing materials [62]. The productivity of solar still was examined by using black granite gravel, Sakthivel and Shanmugasudar [64]. Black granite gravel was sprayed on the basin area with an average thickness of 6 mm to act as energy storage material. The mathematical model was developed to predict the temperature of gravel, glass, and water. Results show that the utilization of black granite gravel observes a 17 to 20% increase in yield. Abdallah et al. [65] studied the effect of thermal energy-absorbing material on

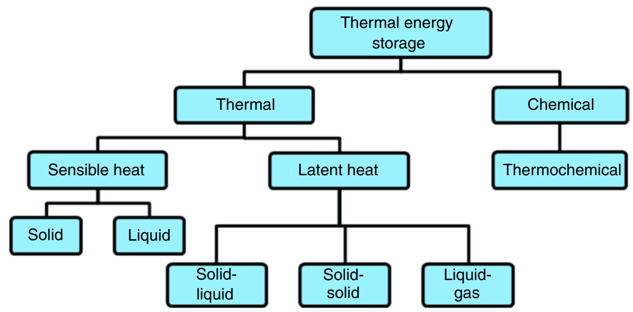

Fig. 10 Different thermal energy storage materials [256] (adapted with permission from ELSEV. B.V. with LIC. No. 4827060462673)

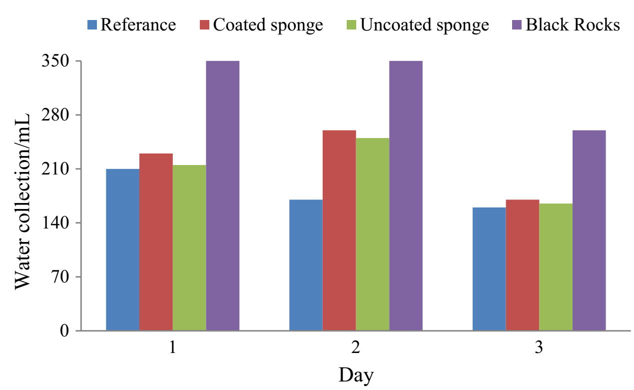

Fig. 11 Water collection by four solar stills in three days [65] (adapted with permission from ELSEV. B.V. with LIC. No. 4827060671855)

solar still. Experimental results show that black rocks absorb the incident radiations better than metallic sponge wire and result in enhanced productivity by 20%. Figure 11 represents the results of experimentation.

Murugavel et al. [66] investigated the effect of wick materials (cotton, jute, sponge) on the performance of solar still. Results show that black cotton cloth offers greater yield as compared to other wick materials. Further, Kalidasa et al. [67] studied the influence of several sensible heat-soaring materials (quartzite rock, red brick pieces, concrete cement, washed stones, and iron scraps) on the productivity of single-basin double-slope solar still. Results show that quartzite rock material offers enhanced productivity as compared to other materials. Nafey et al. [68] investigated the influence of black rubber (energy-soaring material) with variable thickness. Results reveal that enhanced performance is attained by black rubber possessing a thickness of 10 mm.

Further, Kabeel et al. [69] examined the influence of sensible storage material on single-basin solar still. For the experimental study, graphite was used as a sensible storage material due to its high thermal conductivity. Results revealed that daily production of still was around 7.7 L m^{-2} that are much higher than traditional single-basin still. Samuel et al. [70] studied the utilization of low-cost energy storage materials. Theoretical and experimental tests using spherical salt storage material were conducted. Results infer that solar still gave maximum productivity up to 3.7 L m^{-2} compared to conventional single-basin solar still. Omara and Kabeel [71] performed experiments on sand bed solar still using black and yellow sand. Additionally, the effect of the height of sand beds was also studied. Results show that black sand with 0.01 m height gives 42% more yield than conventional solar still, while yellow sand with the same height gives 17% more yield. Figure 12 depicts the cumulative distillate output with different types of sand. In addition to energy storage materials, phase change materials have also been used to improve solar still's productivity. Phase change materials are also called latent heat storage materials because of their unique property of absorbing energy and adapting to physical state change [72]. Paraffin wax is utilized as a phase change material more popularly due to its better thermal properties (specific heat 2320 J $kg^{-1}\,{}^{0}C$; thermal conductivity 0.23 $Wm^{-1}{}^{0}C$; density 802 kg m^{-3}) [73]. Table 5 depicts the summary of phase change materials used on different types of solar stills.

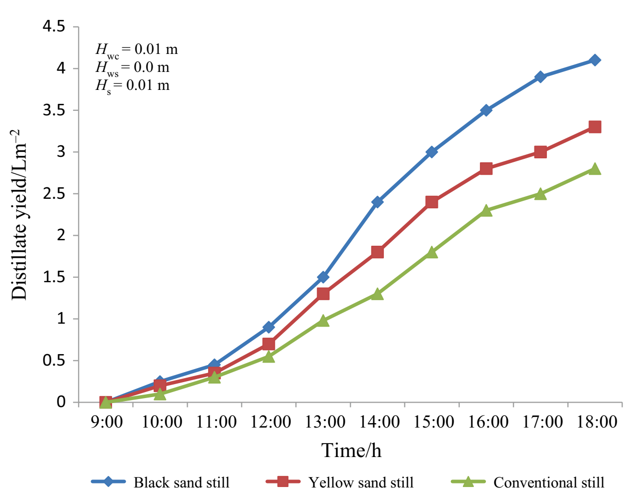

Fig. 12 Cumulative output with different types of sand [71] (adapted with permission from Taylor & Francis with LIC. No. 5032200472931)

Moreover, hybrid nanoparticles are the combination of two or more organic or inorganic components [74, 75]. These materials have gigantic exploration interest due to their special properties, like quantum confinement effect and extremely large surface-to-volume ratios [76]. These nanofluids are utilized for various solar applications like flat plate collectors, parabolic collectors, evacuated tubes, and solar still [77–79]. Nanomaterials' properties depend on their size, shape, and other structure porosity [80]. Gazar et al. [81] assessed the performance of conventional solar still with alumina and copper oxide as a hybrid nanofluid. The result of the experiment inferred a 27 and 21% rise in productivity in the summer and winter season, respectively, with the integration of hybrid nanofluid. Kabeel et al. [82] studied the impact of paraffin wax and graphite nanoparticles as hybrid material on CSS performance. The result shows a 63 to 94% enhancement in productivity.

Effect of insulating material and thickness of insulation

Generally, heat loss occurs from the lower and lateral surfaces of the basin due to the absence of insulation at these surfaces, affecting the overall production. The productivity of any solar still gets decreased due to a large amount of heat loss through the basin and sidewalls of a still. Most of the researchers reported that only 38.40% of solar energy was used for evaporation. The remaining 61.60% of energy gets wasted as heat loss from the solar still. About 35.70 and 25.70% of energy were lost from the glass cover and side-bottom of the still, respectively [83, 84]. Therefore, it is necessary to minimize the heat loss that can be attained by providing adequate padding using different insulating materials. Numerous researchers have widely investigated insulating materials such as sawdust, polyurethane, and gypsum. The research showed that the required thickness of insulation directly depends on insulating constituents' thermal conductance. Solar still productivity improves with an increase in the thickness of insulation depicted in Fig. 13. It is observed that the daily productivity increases from around 1.8 to 3.3 L m^{-2} as the thickness of insulating material increased from 0 to 0.1 m, indicating that proper insulation is necessary to reduce the heat losses and enhance productivity. A detailed summary of insulating materials and the thickness of insulation are presented in Table 6.

Inclination of the cover plate

As discussed in the previous sections, solar still productivity strongly depends on latitude coordinates and the intensity of radiations on saline water [61]. To receive a higher amount of solar radiation from the sun, the solar still covers plate's inclination angle cover plate is a crucial factor that needs to be considered. Most of the investigations revealed that the

Table 5 Summary of phase change materials (PCM) and nanoparticles with various solar stills

References	Type of solar still	Phase change material/nanoparticle	Remarks
[184]	Single-stage	Emulsion of paraffin wax, paraffin oil, and water	Maximum distillate output of 4.536 L m^{-2}
[156]	Stepped	Paraffin wax	Maximum daily productivity of 4.6 L m^{-2}
[185]	Single-slope single basin	Stearic acid	Productivity increases (80.14%) by using phase change materials
[186]	Single slope	Lauric acid	The result shows that during daytime, productivity increased by 30 to 35%, and at nighttime, productivity increases by 127% by the utilization of lauric acid
[187]	Triangular pyramid	Paraffin wax	Results show that 20% increase in productivity by the use of paraffin wax
[188]	Tubular	Stearic acid	The result shows a 20% increase in the output by using phase change materials
[189]	Single slope	Paraffin wax with aluminum powder	Aluminum powder, combined with paraffin wax, reveals good thermal conductivity. Results depict that with higher distillation time, there is a considerable increase in the production of solar still
[190]	Passive	Paraffin wax	Results show solar still production increases by incorporating latent heat storage materials
[52]	Pyramid	Paraffin wax	Production improved by 87% by the use of phase change materials
[191]	Single slope	Magnesium sulfate heptahydrate, sodium sulfate, titanium oxide as nanoparticle	Experimental results show that magnesium sulfate heptahydrate improves output
[192]	Single slope	Potassium dichromate, sodium sulfate and sodium acetate	Productivity of distillation unit enhanced by the utilization of phase change materials
[193]	Single slope	Potassium dichromate, magnesium sulfate heptahydrate, and sodium acetate	Experimental results show that magnesium sulfate heptahydrate gives better performance in comparison with others
[194]	Single slope	Paraffin wax along with Al_2O_3 nanoparticle	Experimental results show that 10.38% increase in daily distillate output when paraffin wax was used, but distillate output increases up to 60.53% when paraffin wax was used along with Al_2O_3
[195]	Evacuated tube collector	Paraffin wax	Experimental results show that daily output reaches up to 6.555 Lm^{-2}. Productivity increases by up to 86% by using paraffin wax
[196]	Parabolic solar collector	Paraffin wax	In summer conditions, productivity increased in the range of 55–65%, whereas in winter, it increased by only 35–45%
[197]	Concentrator coupled hemispherical basin	Paraffin wax	The result shows a 26% productivity increase of concentrator-coupled hemispherical basin still
[198]	Tubular solar still	Paraffin wax	The utilization of paraffin wax enhances productivity by up to 8%
[44]	Conventional	Graphite and copper oxide	The experiments' results depict a 44.91% and 53.95% rise in the productivity of still by utilizing copper oxide and graphite, respectively
[199]	Conventional	Cuprous and aluminum oxides	The outcomes acquired utilizing cuprous oxide and aluminum oxide nanoparticles upgraded the distillate by 93.87% and 88.97%, respectively, compared to those still without nanoparticles

Table 5 (continued)

References	Type of solar still	Phase change material/nanoparticle	Remarks
[200]	Stepped solar still	MgO and TiO_2	Results show an improvement in yield by 41.05% and 61.89% utilizing a 0.2% volume concentration of TiO_2 and MgO nanofluid, respectively
[138]	Concave-type stepped solar still	MgO, Al_2O_3 and TiO_2	Results show a 41.35% enhancement in productivity by the use of MgO nanofluid with 0.2%
[201]	Tubular solar still	Graphene nanoparticle with PCM	The result shows a 116.5% improvement in the efficiency by the utilization of graphene nanomaterial with PCM
[202]	Single-slope solar still	Silica nanoparticles with PCM	Result inferred that productivity of still enhanced up to 67.07% by using silica nanoparticles with PCM
[203]	Thermoelectric-based solar still	Hybrid nanofluid ($Ag@Fe_3O_4$/deionized water nanofluid)	Daily productivity of solar still improved by 218% as compared to conventional solar still
[204]	Single-slope solar still	Al_2O_3/water nanofluid	Results show a 66% increment in the productivity of still

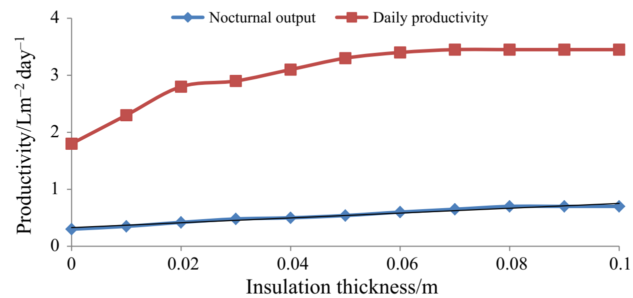

Fig. 13 Effect of thickness of insulation on the productivity of solar still [257] (adapted with permission from ELSEV. B.V. with LIC. No. 4827070493761)

inclination angle must be equivalent to that particular location's latitude so that the maximum intensity of radiations can be achieved throughout the year. Further, it is observed that varying the tilt angle concerning the latitude coordinates decreases the overall productivity (Fig. 14). Table 7 summarizes the inclination angle of the cover plate used for different configurations of solar still. Also, Fig. 15 represents the condensing cover of solar still at different inclination angles. The result depicts the monthly variation of distillate output nearly the same for all the cover plate's inclination angle.

Thickness of cover plate

The thickness of the cover plate and condensing cover material are two other factors that can significantly influence the productivity of solar stills [85]. Highly transmissive materials like glass are widely used as cover plate material for solar stills owing to their high affinity to absorb radiations. Additionally, it is also absorbed that lower cover plate thickness is favored for stills with higher productivity. Figure 16a and b depicts the influence of glass cover thickness and condensing cover materials on the solar still productivity, respectively. Results reveal that maximum solar still productivity is attained with a 2-mm-thick cover plate and decreases with the increase in cover plate thickness. Figure 16b shows the productivity attained with copper, glass, and plastic cover plates. Results show that plastic and glass cover plates possessing lower density can provide productivity similar to copper. Therefore, the cover plate's material and thickness need to be correctly selected to achieve good productivity. Table 8 depicts a review of the effect of cover plate thickness on the productivity of solar still (Fig. 17).

Use of internal and external reflectors

Conventional solar stills have the constraint of low output. Many researchers have worked on the use of reflectors to improve solar still productivity [86]. The use of reflectors comes into consideration when the intensity of radiation

Table 6 Summary of the various insulating materials and insulation thickness

References	Type of solar still	Insulating material	The thickness of insulation/mm	Remarks
[68]	Single sloped	Foam	40	Foam is provided on the bottom and lateral surfaces of the still to reduce the loss of heat
[31]	Double slope	Sawdust	25	7% rise in productivity due to the effect of insulation
[205]	Ground still	Soot layer	25	Solar still productivity improves by 17%
[206]	Inclined humidifier dehumidifier still	Glass wool	10, 50, and 100	Results show a slight improvement in productivity
[207]	Double basin and conventional single slope	Styrofoam	(sides) 25 and (base) 50	For conventional solar still 9% improvement while 33% improvement for double-basin solar still
[208]	Single basin	Sawdust	75	Results reveal considerable improvement in productivity
[209]	Single basin	–	10–50	Results infer that by increasing the thickness of insulation, output improves by 40% in July and 50% in January shown in Fig. 14
[210]	Single basin	Polyester	100	Results depict significant productivity improvement
[211]	Single basin	Styrofoam	100	The bottom and lateral surfaces of the still are insulated to reduce the loss of heat
[212]	Single basin	Fiberglass	50	Considerable improvement is achieved in terms of output of solar still
[213]	Single basin	Thermocole	–	The output from still shows 6% enhancement
[214]	Single-slope solar sill	Air film acts as insulation with polyurethane as a sealant	–	

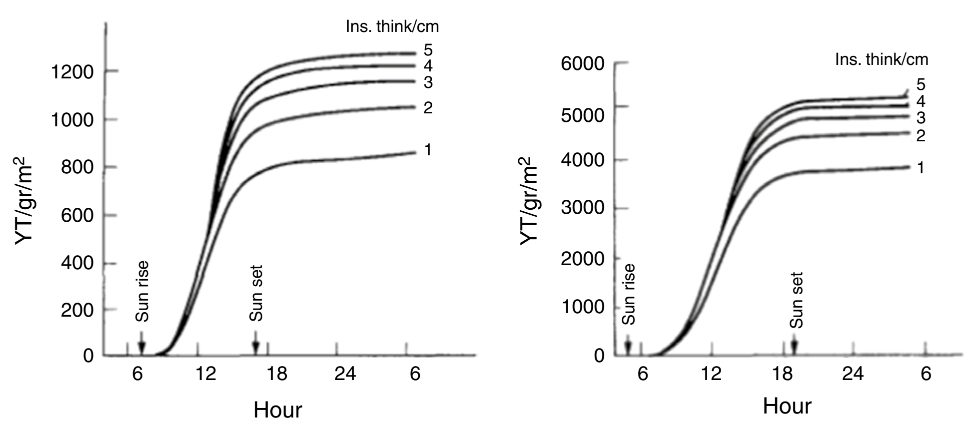

Fig. 14 Effect of thickness of insulation on the productivity of solar still in January and July [209] (adapted with permission from ELSEV. B.V. with LIC. No. 4827070699983)

from the sun is low or the atmospheric temperature is low. There are three types of reflectors, namely internal, external reflectors (top and bottom) and a combination of internal and external reflectors, shown in Figs. 18, 19, and 20, respectively. Internal reflectors are positioned on the inner side of solar still to enhance productivity significantly. These reflectors are used to centralize all the solar radiations onto the water. Tamimi [87] experimented on single-slope solar still. Mirrors were used as internal

Table 7 Summary of the inclination angle of the cover plate with different locations along with remarks

References	Solar still type	Angle of inclination	Latitude of location	Remarks
[100]	Basin type solar still	15°, 25°, 35°, 45°, and 55°	Jordon, 31.949° N	Experimental results show that at a 35° tilt angle, solar still gives maximum distillate output
[215]	Single-basin solar still	10°	Madurai, 9.9252° N	It was seen that solar still productivity improves once the inclination angle is near about equal to that place's latitude
[216]	Solar still	30°	Mehsana, 23.5880° N	Solar still gives better performance with a higher angle of tilt as compared to the latitude location
[212]	Single-basin solar still	45°	Syria, 34.8021° N	Inclination angle ± 10° of latitude can give better results
[217]	Pyramid-shaped and single slope	Pyramid tilt angle 50°	Aswan, Egypt, 24.0889° N	Single-slope type was recommended for such the location where the latitude is higher than 20°
[183]	Active and passive	5°, 15°, 30°, 40°, 45°	Chennai, Jodhpur, Kolkata, Mumbai, and New Delhi	Annual solar still productivity was higher when the inclination angle was equivalent to the latitude of the location
[31]	Double-slope solar still	10°,20°,30°	Madras, 13.0827° N	Better results were obtained at 10°angle of inclination
[218]	solar still with inclined evaporating yute	30°,35°,40°	Egypt, 26.8206° N	Results show that 30°and 35° were the optimum angle of inclination for increased productivity
[219]	Single-basin solar still	50°, 15°, 25°, 35°, 45°, 55°, and 65°	Cyprus, 35.1264° N	The best angle of inclination was 35°, which is equivalent to the latitude of that region
[220]	Single-compartment and double-compartment still	13°, 14.5°, 16°, and 17.5°	Cameroon, 7.3697° N	Better results were obtained when the angle of inclination was 16°

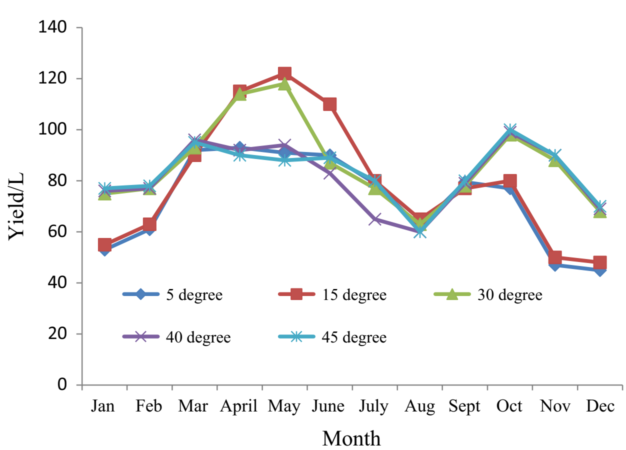

Fig. 15 Variation of inclination angle with annual yield [183] (adapted with permission from ELSEV. B.V. with LIC. No. 4827070896397)

reflectors, located on the inner walls of the still. Results show a considerable increase in solar still productivity.

External reflectors are utilized to improve the direction of radiation beams transmitted through the glass cover. Generally, suitable reflective materials such as mirror-finished metal plates are used to produce external reflectors. Further, there are two types of external reflectors, external top reflectors, and external bottom reflectors depicted in Fig. 19a and b. However, incorporating internal and external reflectors separately has resulted in enhanced productivity [86]. A detailed summary to depict the review of the effect of various reflectors on solar still is presented in Table 9. Incorporating reflector plates, either internal, external, or both, can significantly increase the distillate output in solar stills.

Gap distance between absorber plate and condensing cover

It was observed from various studies that solar still output could be enhanced by reducing absorber plates and condensing cover gaps. If the gap is optimum, saturated fluid

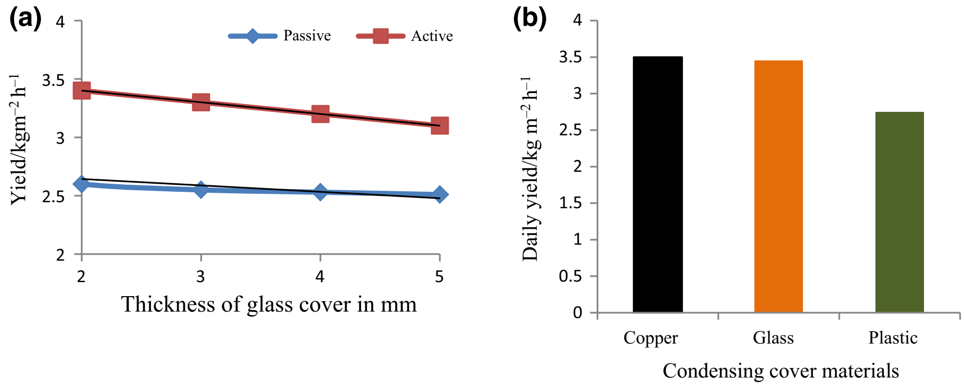

Fig. 16 **a** Effect of thickness of glass cover on yield and **b** effect of condensing cover material on daily yield [167] (adapted with permission from ELSEV. B.V. with LIC. No. 4827071047892 and 4827071198971)

Table 8 Review of the effect of thickness of cover plate over the productivity of solar still

References	Type of solar still	The thickness of the cover plate/mm	Cover material	Remarks
[167]	Active solar still	2, 3, 4, 5, and 6	Copper, glass, plastic	Experimental results show at 2 mm thickness of the cover plate, and productivity was higher. Copper provides a higher yield in comparison with glass and plastic owing to their high thermal conductivity
[28]	Single-basin solar still	3, 5, and 6	Glass	3-mm glass cover gives maximum productivity up to 15.5%
[221]	Passive single-slope single basin	4, 8, and 12	Glass	Results show that the thinnest glass cover gives higher distillate output
[222]	Double-slope solar still	3, 4, and 5	Glass	Experimental results revealed that 3 mm thickness of glass cover gives a better productivity
[140]	Pyramid-shaped solar still	3	Glass	3 mm glass thickness was considered for better output
[223]	Finned acrylic solar still	4	Glass	4 mm glass thickness was considered for better output
[224]	Domestic scale solar still	–	Transparent PVC sheet	The experiment's outcome depicts the productivity of still with PVC sheet found to be less (42% less) compared to the glass material
[85]	Single-basin solar still	4, 5, and 6	Glass	Results show that 4-mm and 6-mm-thick glass cover provides 27 and 12% higher yield when contrasted with 6-mm-thick cover. Results of the experiment are shown in Fig. 17

will reach the condensing surface in less time, enabling to improve the continuous air movement [88]. Keshtkar et al. [88] performed CFD modeling to observe the impact of gap distance between the cover plate and basin of a solar still. The investigation inferred at a gap distance of 8 cm still provides the highest distillate out than the 4 and 12 cm gap. Therefore, it was presumed that to achieve maximum productivity from solar still, the gap between cover and surface of water basin essentiality is optimum. Outcomes of the experimentations are depicted in Fig. 21.

Rahbar and Esfahan [89] analyzed the effect of gap distance on the single-basin solar still production theoretically and numerically. Results inferred that when the height of the solar still was minimized, the distance between the glass cover and water surface also gets minimal, thereby improving the convective heat transfer coefficient and, therefore, an enhanced condensation rate. Jamil et al. [90] investigated the effect of varying the gap plate distance on solar still productivity. Figure 22b shows the gap distance between the absorber and condensing surface. H1 was the highest gap distance, while H4 was the lowest. Experimental results for the varying gap are shown in Table 10. Results revealed that productivity gets enhanced by maintaining optimum gap distance. The gap distance between the glass cover and water surface is minimum (in the case of H3 and H4), which improves the convective heat transfer coefficient and thus

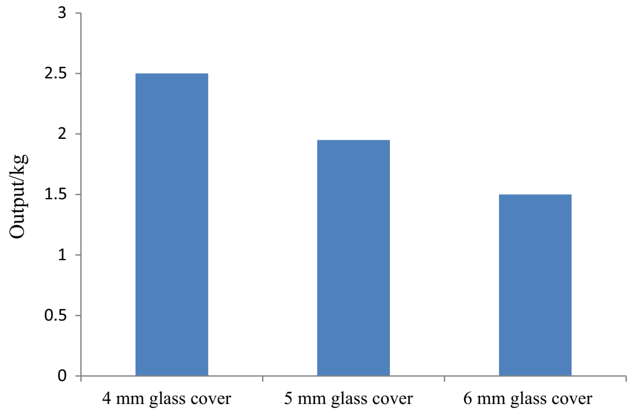

Fig. 17 Effect of thickness of glass cover on output [85] (adapted with permission from Springer with LIC. No. 5032200235394)

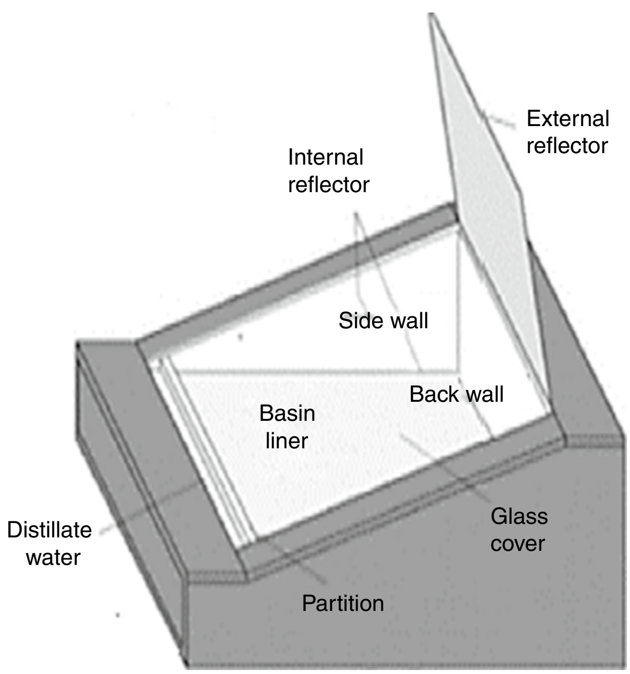

Fig. 18 Internal and external reflector [258] (adapted with permission from ELSEV. B.V. with LIC. No. 4827091362308)

increases condensation rate, leading to improvement in solar still performance. The optimum gap between absorber plates and condensing cover needs to be considered in detail to have higher productivity of solar stills.

Sun tracking system

The primary purpose of the development of a sun tracking system is to enhance solar still productivity. One can increase the incident solar radiations on still by tracking the sun's location in the sky. The slant angle of the sun is one of the vital factors in solar applications [91]. Sun tracking system is a computerized device that rotates solar still direction as per the sun's movement. Mainly there are two types of sun trackers, namely, single-axis tracker and dual-axis tracker [92]. Single-axis trackers can track the sun only from East to West direction, while dual-axis trackers can track the sun's location on any day and anytime. From most of the literature, it was clear that the sun tracking system enhances solar still productivity when compared with a fixed system. Maliani et al. [93] and Abdelghani [94] demonstrated that with the sun tracking system's utilization, the temperature of the water increases quickly. Abdallah and Badran [95] found out that a 22% improvement in solar still productivity was observed by incorporating a sun tracking system. Figure 23 shows water collected for both fixed still and still with a sun tracking system. Khalifa and Mutawalli [96] used a two-axis sun tracking system and concluded that a 75% improvement in solar still performance could be attained. Abdallah and Nijmeh [97] worked on a two-axis sun tracking system; results show that a 41.34% increase in collected solar energy on the water's surface was achieved. Abdallah et al. [98] investigated modified design of single-basin system with sun tracker. Results show that stepwise basin with sun tracking system gives highest thermal performance of 380%. Sun tracking system can be affective to increase the productivity of solar stills.

Operational parameters

Various operational parameters that affect productivity are listed below.

- The salt content of water
- The flow rate of water
- Use of dyes
- Others

Salt content of water

The concentration of salt present in the water is known as the salinity of water [99]. Generally, the salinity of salt is measured in g(salt) kg^{-1}(seawater). From various literature, it is observed that the productivity of solar still declines by increasing salt concentration in the water. Bilal et al. [100] studied the effect of salinity of water on basin-type solar still. Results show that the salinity of water reduces solar still productivity, as depicted in Fig. 24. Hoque et al. [101] studied the effect of salinity of water on solar still productivity with synthetic saline water. Results show that with increasing total dissolved salts (TDS) value from 2000 to 8000 ppm, the productivity of solar still declined by 7.8%. Shirsatha et al. [102] studied the effect of salinity of water on doubly inclined solar still and concluded that solute in

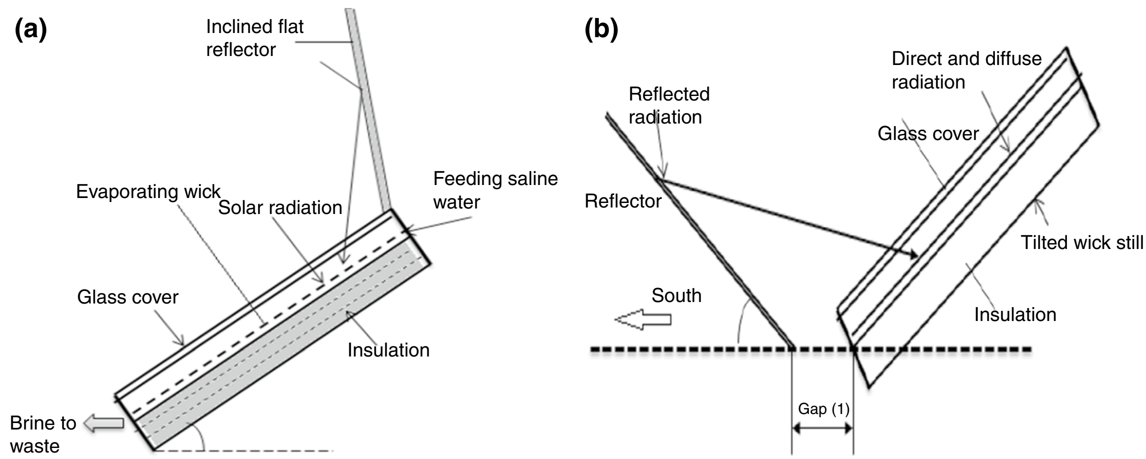

Fig. 19 (a) Top and (b) bottom external reflector [259] (adapted with permission from ELSEV. B.V. with LIC. No. 4827100328386)

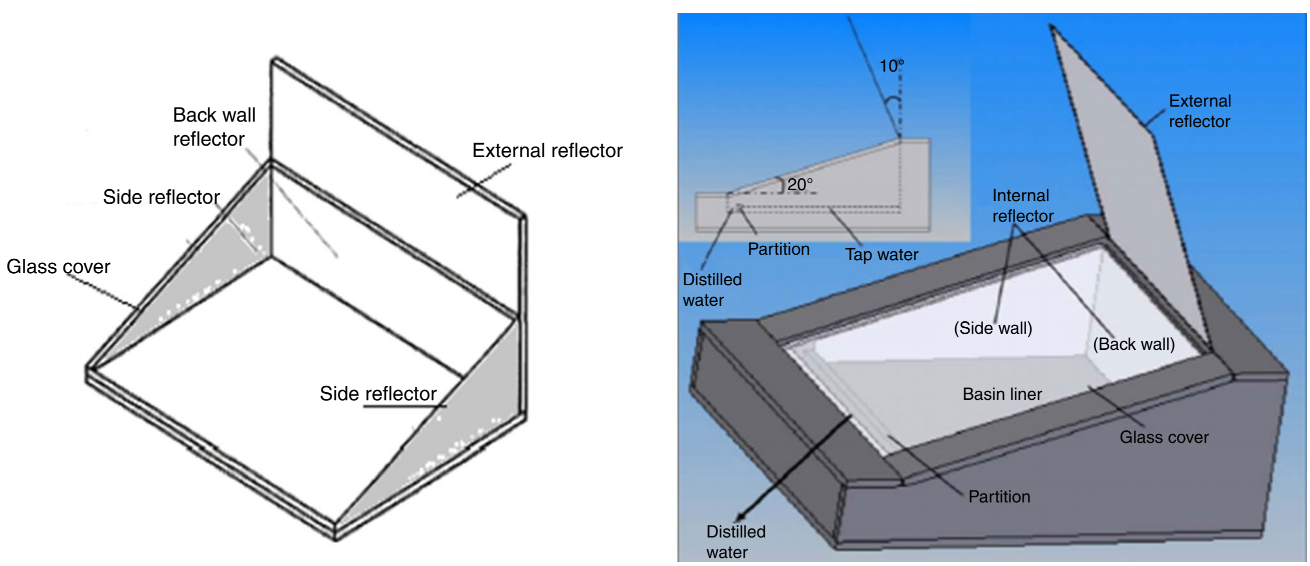

Fig. 20 Combined internal and external reflector [260] (adapted with permission from ELSEV. B.V. with LIC. No. 4827100874630)

water decreases solar still productivity. Mahdi et al. [103] conducted the experiments on wick-type solar still. Results show that at 2.50% of saline water, efficiency was 39%, while for 5.00% saline water, efficiency was 33%. Further, it was also concluded that the efficiency of solar still decreases linearly with increasing salt concentration. Rai et al. [104] experimented on single-basin solar still and found out that an increase of salt concentration in water increases the surface tension and reduces the evaporation rate, and leads to a decrease in productivity.

Flow rate of water

From most of the literature, it was found that the efficiency of solar still declines as the flow rate of water increases [105]. Tabrizi et al. [106] designed weir-type cascade solar still and studied the effect of water flow rate on productivity and internal heat and mass transfer. Results show that a decrease in the productivity and rate of heat and mass transfer was observed with increasing flow rate. When the mass flow rate was 0.065 kg min^{-1} and 0.2 kg min^{-1}, the productivity was 7.4 kg m^{-2} and 4.3 kg m^{-2}, respectively. Kerfah et al. [107] studied the effect of the volumetric flow rate of water on the evaporation rate and found out that the evaporation rate was maximum at a minimum volumetric flow rate ($3 \times 10^{-6} m^3 sec^{-1}$). Mahdi et al. [103] designed wick-type solar still and studied the effect of water flow rate on efficiency. Results illustrate that solar still efficiency decreases as the flow rate of water increases, as shown in Fig. 25. Further, Suneja and Tiwari [108] studied the effect

Table 9 Review of various reflectors effect on the performance of solar stills

References	Type of solar still	Reflector material	Effect of the reflector/%	Remarks
Internal reflectors				
[98]	Conventional solar still	Mirror	30	A 30% increase in efficiency is observed. The use of reflectors can provide a daily output of 1.64 kg m^{-2}
[225]	Conventional solar still	Stainless still	25–35	Incorporating cylindrical stainless-steel internal reflector, solar still efficiency increases by 25–35%
[226]	Stepped	Mirror	18	The efficiency of stepped still with reflector increases by up to 75% as compared to conventional ones
[227]	Conventional solar still	Mirror	34	The use of internal reflectors helps to improve solar still productivity by 34%
[228]	Wick type	Mirror	55	Daily distillate output was found to be 4.1 kg m^{-2} by using internal reflectors
[178]	Conventional	Mirror	20	Result reveal 11% rise in efficiency is attained by using internal reflectors
[86]	Basin type of solar still	Mirror	20	Results show a 19.9 and 34.5% rise in productivity when still was compared with no reflectors
External top reflector				
[229]	Conventional	Mirror	45	Results depict enhancement in solar still productivity is achieved by incorporating mirror as an external top reflector
[230]	Tilted wick	Mirror	15	Solar still productivity improves by the utilization of inclined reflectors. Result reveals that productivity improves 15%—27% by the utilization of inclined reflectors
[231]	V-type of solar still	Mirror	7.3	Results show that 2.7 kg m^{-2} daily output is achieved and 7.3% improvement in the solar still efficiency
External bottom reflector				
[232]	Inverted absorber solar still	Steel	200	Results show that daily distillate output was 6.3 kg m^{-2}
[233]	Double-slope solar still	Mirror	82	82% improvement in efficiency was observed
[234]	Double-slope single-basin solar still	Mirror	19 and 30	19 and 30% improvement in efficiency is achieved in summer and winter conditions, respectively
[235]	Tilted wick solar still	Mirror	13	Results show a 13% increment in the solar still productivity
Combined internal and external reflectors				
[236]	Conventional solar still	Mirror	42	The productivity of solar still with an internal and external reflector was 42% higher than conventional solar still
[237]	Conventional solar still	Mirror	145	Results show on winter days. There was a significant enhancement in the solar still output
[238]	Portable thermoelectric solar still	Aluminum foil	43	5 kg m^{-2} distillate output per day was achieved. Solar still output increased by 43%
[239]	Conventional solar still	Mirror	72.8	Solar still productivity shows enhancement by use of a mirror as an internal and external reflector
[240]	Stepped solar still	Mirror	77	Daily productivity of 7.4 kg m^{-2} is achieved

of water flow rate over the condensing cover of solar still and concluded that a particular flow rate of water evaporative heat transfer coefficient declines.

Use of dyes

In the case of a conventional solar still, heat is transferred from the bottom to the water's surface with the convection mode of heat transfer [109]. As previously discussed, higher intensity of solar radiations enhances the productivity of solar still. Therefore, to gain a large amount of solar radiation from the sun, a dye is mixed with water to absorb maximum radiation from the sun. Cooper [110] reported that to improve solar still productivity, it is necessary to improve water's absorptivity, which can be improved by adding blue and red dyes in water. Results of the study show that the addition of dyes can improve the absorptivity of the water. Sodha et al. [111] and Pandey [112] studied the effect of

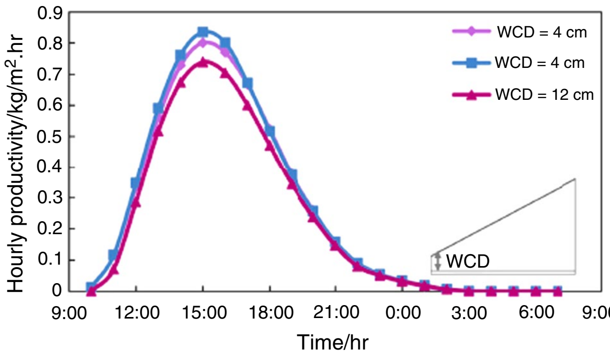

Fig. 21 Impact of gap distance on the productivity of still [88] (adapted with permission from ELSEV. B.V. with LIC. No. 4827101056725)

Table 10 Experimental results of gap distance between the absorber and condensing surface

Sl. No	Gap distance/H	Distillate output/mL	Distillate output/%
1	H1	1260	55.87
2	H2	1964	83.49
3	H3	2312	–
4	H4	2695	

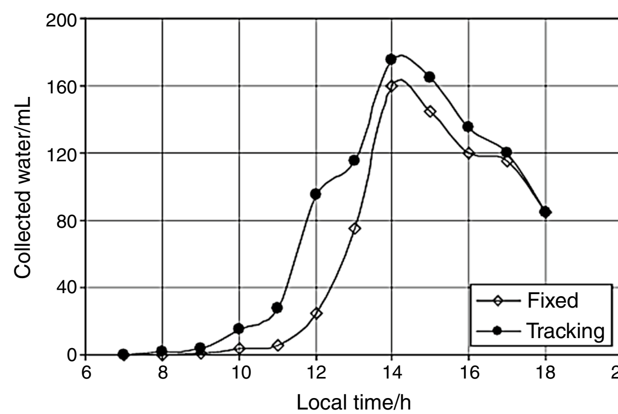

Fig. 23 Collected water for both fixed still and still with sun tracking system [95] (adapted with permission from ELSEV. B.V. with LIC. No. 4827101365161)

dye on solar still productivity. Results show productivity enhances with dye's addition as the dyes help improve the evaporation rate shown in Fig. 26. As a result of this, an increase in distillate output is observed. Rajvanshi [113] studied the effect of black naphthylamine, red carmoisine, and dark green dyes at various concentrations. Results show that 29% rise in solar still productivity is attained when black dye with 172.5 ppm was used.

Other techniques

So far, we have discussed climatic, design, and operational parameters that affect solar still performance. In this section, we will discuss some other modifications done by various researchers on solar still. The performance of the solar still can be improved by preheating the inlet water [114]. The condensation and evaporation rate of preheated water is more than ordinary water [115]. Various techniques are utilized to preheat water, which includes integration of solar ponds, heat pipe, and flat plate collector [116–120]. Preheating water is mainly performed by passing the water over a solar panel before the solar still basin. Elbar and Hassan [121] assessed the performance of solar still by preheating the saline water. The experimental work results show preheating 60% of the saline water upsurge the productivity by 20.9%, contrasted with sun-powered desalination framework without preheating. Subramanian et al. [122] utilized a flat plate collector for preheating the saline water in modified pyramid solar still. Results of the experiment depict a 60% rise in productivity compared to ordinary solar still. From the above literature work, it is concluded that preheating helps to enhance the water temperature. When the higher temperature water is passed through the basin of a still, the heat needed for evaporating the saltwater is less, and hence the profitability is increased. Refalo et al. [123] utilized the

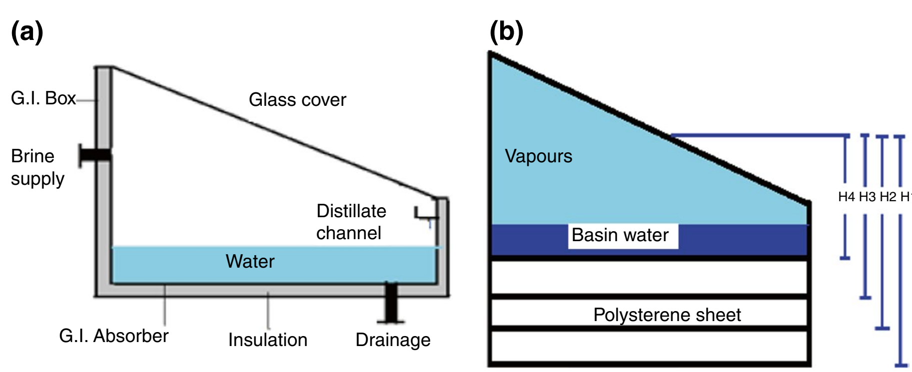

Fig. 22 **a** Conventional single-slope solar still and **b** gap distance between absorber and condensing surface [90]

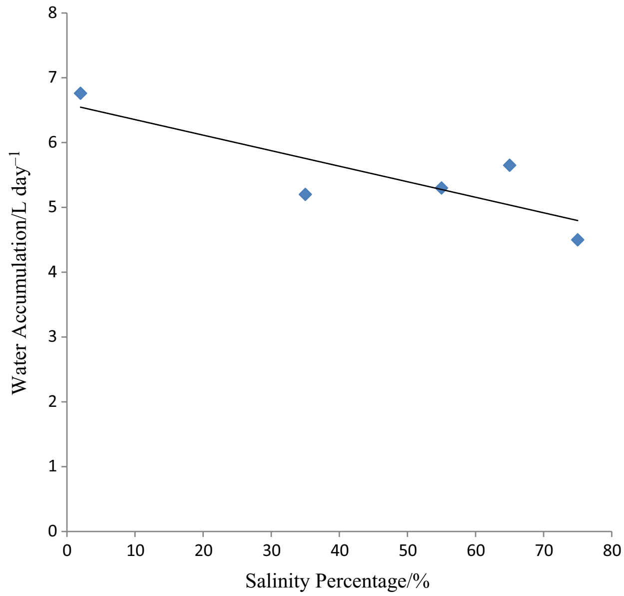

Fig. 24 Effect of salinity of water on daily water accumulation [100] (adapted with permission from ELSEV. B.V. with LIC. No. 4827111118425)

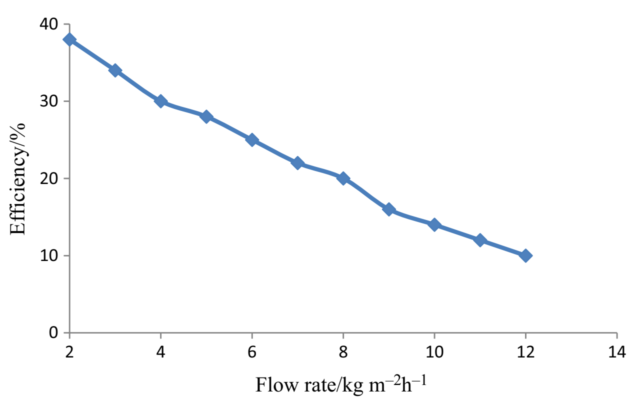

Fig. 25 Effect of the flow rate of water on the efficiency of solar still [103] (adapted with permission from ELSEV. B.V. with LIC. No. 4827111258653)

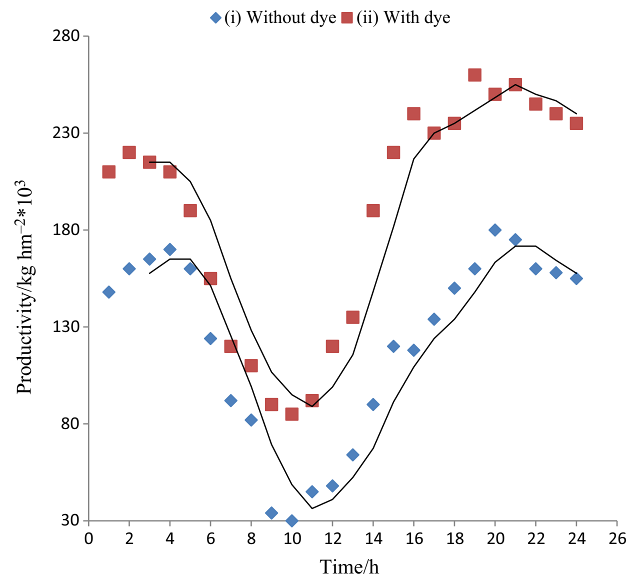

Fig. 26 Variation of productivity with and without dye [111] (adapted with permission from ELSEV. B.V. with LIC. No. 4827120038517)

solar chimney within solar still in association with copper pipe condenser. Solar chimney and condenser were utilized to enhance convective heat transfer and rate of condensation, respectively. Figure 27 depicts the solar still with the utilization of chimney and condenser. Results show considerable enhancement in productivity (5.1 L m^{-2} day^{-1}) of still.

A large portion of research work demonstrated that the combination of wick material with a suitable absorber plate design gives a large amount of distillate yield [124]. In the case of a wick-type solar still, the sun-oriented radiation falling on the glass cover passes through it and arrives at the wick surface, where it is absorbed. A portion of the energy is used for warming the water coursing through the wick because of capillary action[125]. Much heat gets caught inside the still, and an exchange of energy occurs from the wick surface to the glass cover and to the surrounding air [126]. Agrawal et al. [127] utilized black jute cloth inside the basin of solar still that offers a large amount of surface area for the evaporation. Results of the experiment inferred a 62% improvement in productivity as compared to CSS. Ahmed and Ibrahim [128] studied the effect of five different wick materials on CSS performance. The experiment results show that black cotton sheet is the most effective wick material as it provides 36.9% enhancement in productivity compared to CSS. The impact of four different wick materials on pyramid solar still performance was carried out by Saravanan and Murugan [129]. For the experimentation purpose, polyester, terry cotton, jute cloth, and woolen fabric were selected. The experiment results show productivity improved by 9.4%, 20.9%, and 33.1% utilizing woolen fabrics than jute, terry cotton, and polyester, respectively.

Experimental and theoretical analysis of solar still was assessed by Mahian et al. [130] by utilizing a heat exchanger with silicon dioxide and copper nanoparticles. Figure 28 depicts solar still with a heat exchanger. The results of the experiment inferred that the utilization of a heat exchanger with nanofluid is advantageous. Furthermore, it was concluded that copper/water nanofluids give better performance than silicon dioxide/water owing to its higher thermal conductivity. Solar flat plate collector is mainly utilized to convert solar energy into thermal energy [131, 132]. Halima et al. [133] numerically investigate the performance of solar still combined with heat pump. The utilization of the heat pump was advantageous for enhancing the temperature of

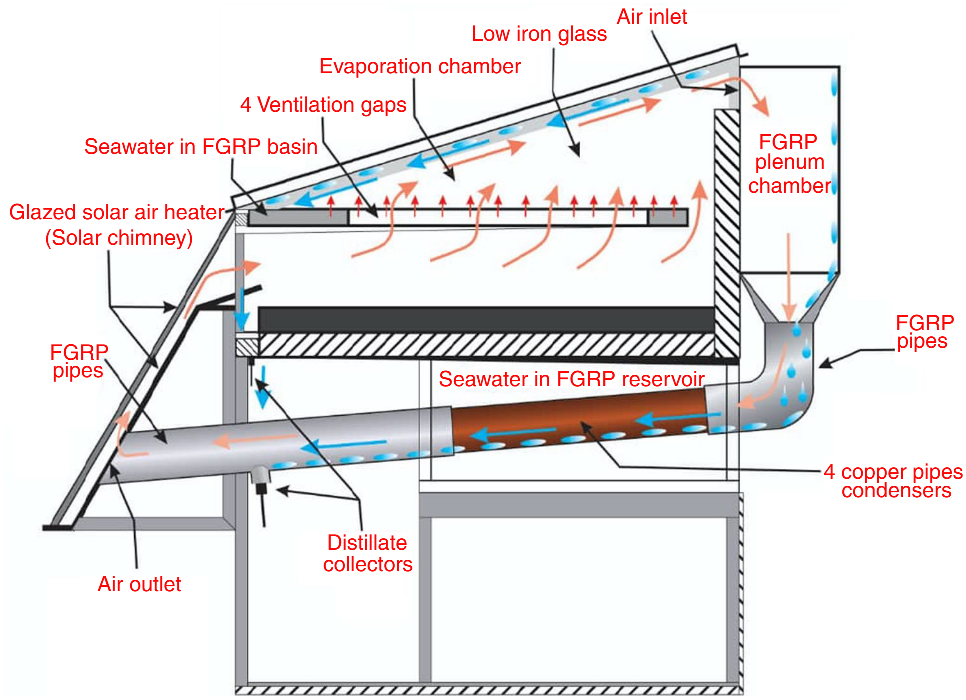

Fig. 27 Solar still with chimney and condenser [261] (adapted with permission from ELSEV. B.V. with LIC. No. 5030780458402)

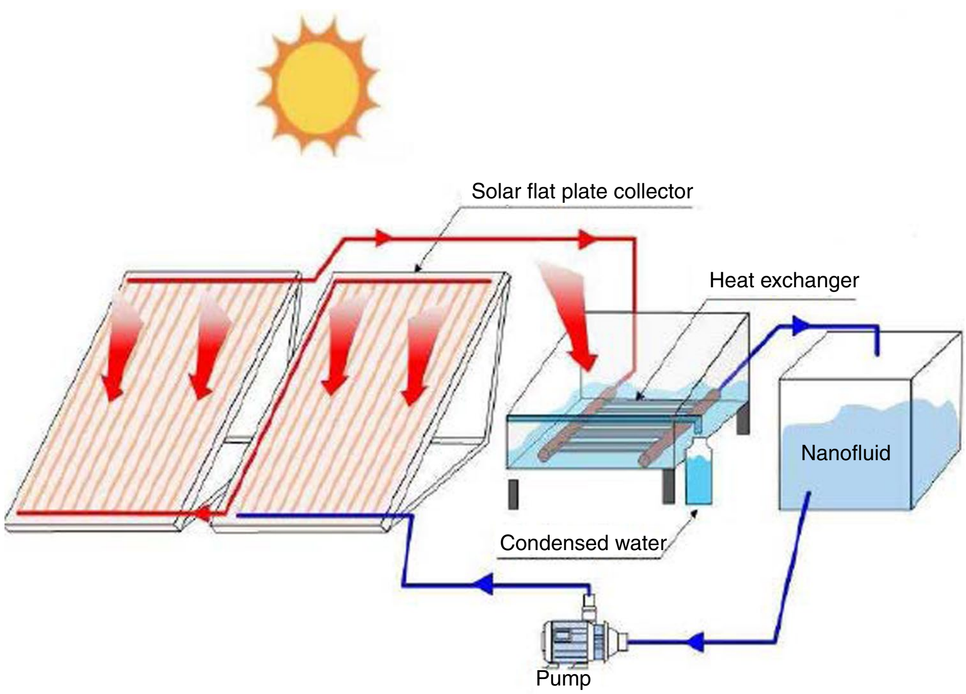

Fig. 28 Schematic layout of solar still with heat exchanger [130] (adapted with permission from ELSEV.B.V. with LIC. No. 4827120260851)

the water. Figure 29 depicts the layout of solar still with heat pump. Results reveal a 75% enhancement in the productivity of proposed still when contrasted with conventional solar still. Shatat and Mahkamov [134] experimentally investigate multistage solar still performance in association with the evacuated solar collector, as shown in Fig. 30. The experiment's results depict productivity of the proposed still was found to be 5 kg m^{-2} day, which is significantly higher than conventional still.

Rabhar and Efahani [135] investigated portable solar still by the utilization of thermoelectric modules. These modules enhance the temperature difference between glass cover and basin surface; consequently, solar still productivity increases significantly. Figure 31a depicts the schematic layout of

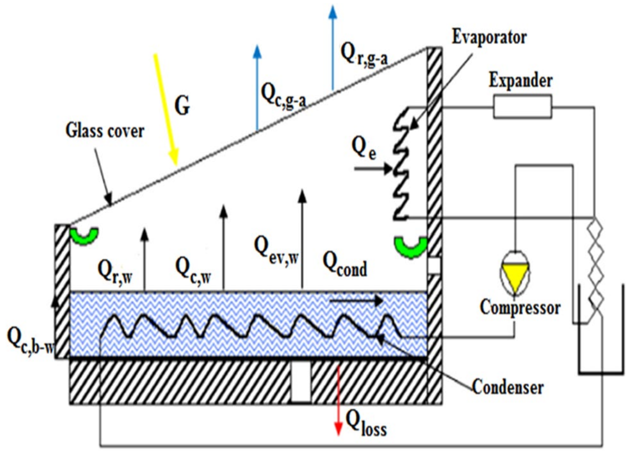

Fig. 29 Solar still integrated with heat pump [133] (adapted with permission from ELSEV. B.V. with LIC. No. 4827120405908)

solar still experimental setup with the thermoelectric module. Results of the experiment reveal the daily efficiency of still was 7%. Somwanshi and Tiwari [136] studied the impact of cooling glass cover in association with the cooling water from the desert cooler (Fig. 31b). The flow of cold water helps to increase the temperature difference between condensing and evaporative areas. The experiment tested for Jodhpur, and Chennai's climatic conditions reveal that yearly productivity increases up to 7.4 and 9.9%, respectively. Table 11 depicts the review of various modifications and their effect on the productivity of solar still. The profitability of a still is affected by the temperature distinction among condensing and evaporative surfaces. Growing the distinction between water–glass temperatures improves the profitability still [137]. To keep up this temperature distinction high, fans, condensers, and glass cover cooling was used. Constant supply of air or water film over the glass cover leads to reduce the temperature of glass [138]. Patel et al. [139] assessed double-slope solar still incorporation with a separate cooling coil condenser. The entire vapors generated during the evaporation process are condensed due to the integration of the cooling coil condenser that leads to enhance the productivity of still. Kabeel and Abdelgaied [140] studied the impact of glass cover cooling on pyramid solar still. The experiment's result shows daily efficiency of solar still with cooling cover improves by 97 to 98% compared to traditional pyramid still.

As of late, attention has been pinpointed around the improvement of different designs of solar still. Pyramid solar still is one of the results of such advancement [141]. The top cover's shape seems to a pyramid; hence, these stills are popularly known as pyramid still. Triangular and square are the two basic types of pyramid solar stills. Madhhachi and Smaisim [142] designed and tested square pyramid solar still. The performance of the solar still was measured for the four seasons in Iraq. Results of the experiments show a 60% rise in the efficiency of design still compared to others. The impact of insulation and water depth on pyramid solar still performance was studied by Muthu Manokar et al. [143]. The experiment was mainly conducted with varying water depth from 1 to 3.5 cm and providing the insulation. The experiment

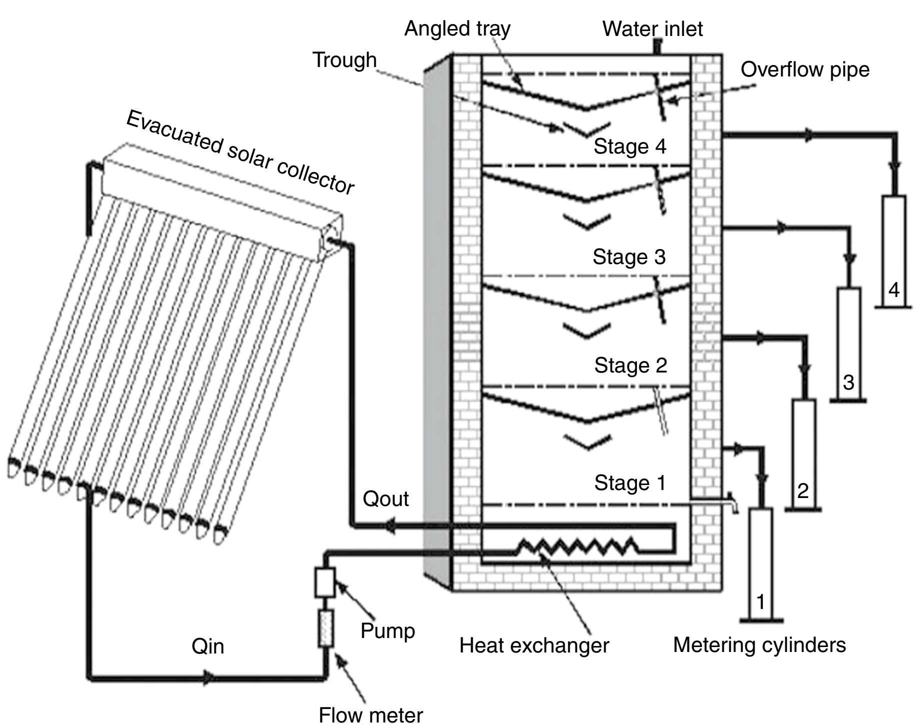

Fig. 30 Schematic layout of multistage solar still with evacuated solar collector [134] (adapted with permission from ELSEV.B.V. with LIC. No. 4827120535708)

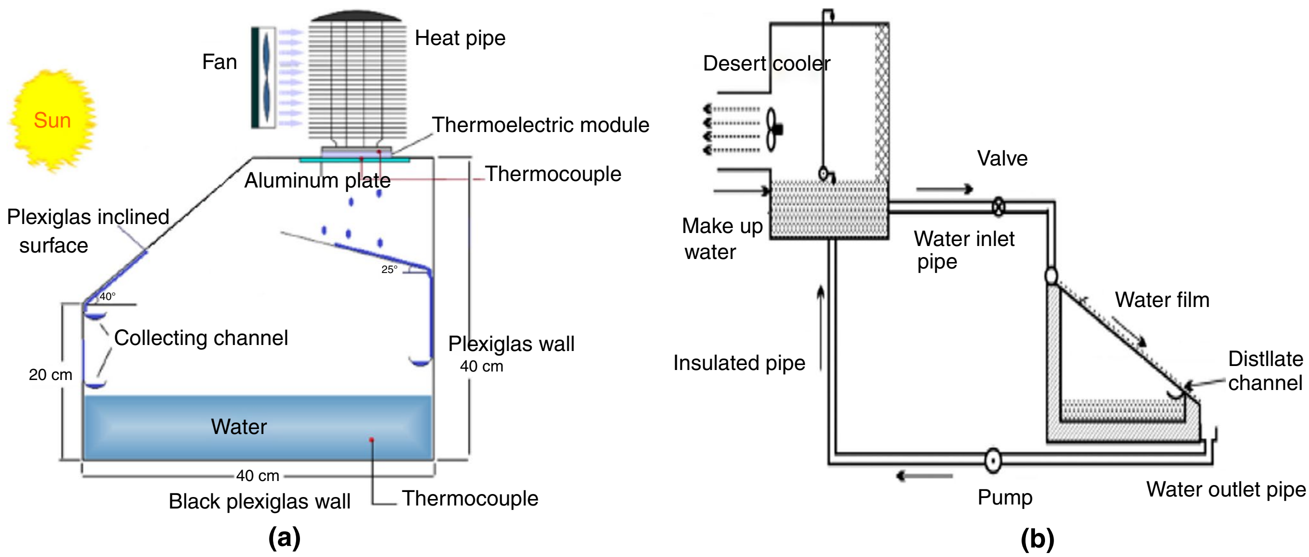

Fig. 31 **a** Still with a thermoelectric module and **b** still with desert cooler [136] (adapted with permission from ELSEV. B.V. with LIC. No. 4827120659991 and 4827120788850)

results show at 1 cm water depth and still with insulation provides the highest distillate output, which seems to be improved by 19.46% compared to single-basin solar still. The impact of granite material, forced evaporation, and forced condensation on pyramid still was studied by Modi and Nayi [144]. Experimental results inferred still with forced evaporation, and granite material provides the highest yield (2.25 L m^{-2}) and is more efficient. The pyramid solar still performance with the integration of evacuated tubes and nanoparticles was studied by Sharshir et al. [145]. The experiment results show improvement in productivity by 27.85% and 33.59% by utilizing copper oxide and carbon black, respectively.

Conclusion and future recommendations

In the present article, a review of various factors affecting the productivity of solar stills is discussed. A review of solar stills is carried out considering the climatic conditions, design, and optional parameters of solar stills. The following conclusions are drawn from the study.

- Combining the good intensity of solar radiations, solar still type and regions with high temperature can provide better productivity in daily distillate output.
- Productivity can be enhanced by increasing the wind velocity from 0 to 10 ms^{-1} to about 50%.
- The presence of dust and dirt particles on the condensing surface reduces the glass cover's transmission capacity. Therefore, condensing cover must be cleaned regularly.
- Maximum productivity can be attained with inclined solar stills when the inclination angle is made equivalent to that location's latitude. The maximum intensity of radiations can be achieved throughout the year by inclining the cover of still equivalent to the location's latitude.
- Aluminum material with nominal thickness can be used as basin material due to its thermal conductivity and corrosion-resistant abilities.
- Minimum depth of water around 1 cm for conventional solar still enhances evaporation and provides higher productivity.
- The rate of evaporation increases with an increase in the surface area of the absorber plate. A stepped basin will provide a higher surface area. The utilization of fins can also improve surface area.
- For better distillate output of solar stills during the low intensity of radiations, energy storage materials (graphite, black rubber, and quartzite rock) and phase change materials (paraffin wax, lauric acid, and stearic acid) are widely used.
- An increase in the thickness of insulating material reduces heat losses in solar still and thereby enhances productivity. Foam, sawdust, and thermocol are widely used insulating materials
- Highly transmissive materials like glass are widely used with minimum thickness up to 3 to 4 mm
- Reflector plates, either internal, external, or both, can significantly increase the distillate output in solar stills.

Table 11 Review of various modifications and their effect on the productivity of solar still

References	Type of solar still	Modification	Remarks
[241]	Solar still	Use of storage tank	Coupling the storage tank to the solar still helps increase the temperature of saline water and enhance the temperature difference between the surface of saline water and the condensing cover
[242]	Water desalination system	Use of low-grade solar heat	Experimental results show that this system's performance is a better one compared to flat basin solar still
[43]	Single-slope solar still	Use of asphalt basin liner and sprinkler	Results show that the use of sprinklers helps to enhance the temperature difference between water and glass cover. 29% increase in output is attained using asphalt basin liner
[243]	Double-slope active solar still	Use of flat plate collector	51% higher yield was obtained from double-slope active solar still
[244]	Solar still	Integration of evacuated tubular collector	Results show that distillate output was 630 kg m^{-2} year, which was higher than single-slope solar still
[117]	Solar still	Integration with mini-solar pond	Results show that a considerable rise in solar still productivity was attained when it was integrated with a mini-solar pond
[245]	Single-slope solar still	Use of a solar heating system	It was found that solar still performance enhances considerably by the use of a solar heating system
[246]	Modified solar still	Use cuprous oxide nanoparticle along with sprinkler attachment	Productivity was improved and found to be 4.0 L m^{-2} day^{-1}
[247]	Solar still	Use of forced convection	The productivity of still was increased by 30%, and forced convection increases heat and mass transfer coefficient
[248]	Double-basin solar still	Integrated with flat plate collector using thermosyphon and forced circulation of water	It was found that the performance of the forced circulation mode was better
[249]	Glass basin solar still	Use rectangular hollow fins for preheating purposes	Use of fins helps to increase the productivity of solar still up to 3.61 kg day^{-1}
[250]	Portable solar still	Use of sprinkler and thermoelectric cooling technique	Results show the rate of condensation, and the rate of evaporation enhances significantly
[251]	Double-basin solar still	Utilization of vacuum tubes	The outcome of the investigation shows a 56% enhancement in the output of solar still, contrasting other researchers' results
[252]	Single-basin single-slope solar still	Utilization of agitation effect and external condenser	The agitation effect was utilized to enhance the contact area between water and air. Moreover, the experiment results show a 39.49% increase in productivity was observed in contrast with conventional still
[253]	Hybrid PV/T active solar still	Use of Peltier system	Results reveal a 30% enhancement in the proposed solar productivity still when contrasted with conventional passive still
[254]	Conventional still	Utilization of rotating drum	Drum assists in enhancing the evaporative surface and abatement the thickness of the saline water film. The results of the experiment show a significant enhancement in productivity (350%) of still
[255]	Single-slope single-basin solar still	Use of PCM and hot air injection	Results show a 108% enhancement in productivity when contrasted with conventional still

- The performance of solar still can be improved by minimizing the gap between absorber plates and condensing cover.
- Incorporating a sun tracking system, either single or dual axis in solar still, can enhance productivity.
- Higher salinity and mass flow of water decrease the efficiency of solar stills.
- The use of dyes on the surfaces of solar still can also increase productivity.

The outcomes reported here offer a way to enhance the productivity of solar stills by considering the feasibility of incorporating advantageous modifications and avoiding the disparaging ones. The most noticeable challenge is to enhance the productivity of still by reducing the losses from the still. In view of the literature survey, researchers need to concentrate on the following areas:

- Broad experimentation is required to recognize the impact of various configurations of the still with heat transfer and thermodynamics.
- The software improvement is required to demonstrate and simulate solar stills concerning various discussed parameters.
- In the case of a stepped solar still, the impact of changing the shape of steps needs to be observed with sensible heat storage materials (SHM) and nanoparticles.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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