

Review

Updates on Evaporation and Condensation Methods for the Performance Improvement of Solar Stills

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Citation: Fu, H.; Dai, M.; Song, H.; Hou, X.; Riaz, F.; Li, S.; Yang, K.; Ali, I.; Peng, C.; Sultan, M. Updates on Evaporation and Condensation Methods for the Performance Improvement of Solar Stills. *Energies* **2021**, *14*, 7050. <https://doi.org/10.3390/en14217050>

Academic Editor: Lyes Bennamoun

Received: 15 September 2021

Accepted: 23 October 2021

Published: 28 October 2021

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Abstract: Solar still, a small equipment using evaporation and condensation processes to get clean water, is expected to be widely used for sea/brackish water desalination, water purification, and wastewater treatment because of its convenient carrying, friendly environment, and low energy consumption. In recent years, considerable progress has been made in improving the productivity of solar still. This paper will reclassify the methods to improve the solar still by elevating the evaporation rate and condensation rate. The main methods increasing evaporation rate are as follows: (i) adding heat storage materials; (ii) using nanoparticles; (iii) changing structure of the absorption plate; and (iv) using photothermal materials. The primary methods increasing the condensation rate are as follows: (i) cooling the condensing surface; (ii) increasing the condensation area; (iii) changing the wettability of the condensing surface; and (iv) using a separate condenser. The advantages and disadvantages of each method are compared. Furthermore, this paper includes an economic analysis of current solar stills and a forecast of future developments. The freshwater cost of solar still is in the range of about USD 0.0061–0.277/L, which provides reference and direction for future researching solar stills on their low cost and high productivity.

Keywords: solar still; productivity enhancement; evaporation rate; condensation rate; review

1. Introduction

Water is essential for the survival of animals and plants. 71% of the Earth is covered by water, but 97% of the water is in the form of seawater, which is undrinkable due to its high salinity. The pollution of surface water and groundwater has caused an increasingly serious shortage of drinking water. In China, 31.4% of the river water quality is grade IV or lower, which is not suitable for drinking. In recent years, the scale of groundwater pollution has also shown a trend of gradual expansion, while remediation of deep groundwater pollution takes a long time [1]. China is one of the 13 water-scarce countries in the world, and its water resources are unevenly distributed [2]. North China suffers from water

scarcity throughout the year, while South China experiences seasonal water shortages due to low water quality. Furthermore, because of the uneven distribution of the population, more than half of 1.36 billion Chinese people suffer from a combination of quantity and quality water shortage [3]. Seawater desalination, as an important method to increase water resources, has been of concern.

The industrial application of seawater desalination technology began in the 1950s, which has become an important method to solve the current water resources crisis in China [4]. However, the high energy consumption of seawater desalination, greenhouse gas emissions, high water footprint, and high-cost problems hinders the further development of industrial applications [5]. At present, renewable energy is recognized as an effective method to solve these problems. Among them, solar energy is clean, unlikely to produce greenhouse gases, easily accessible in different locations, safe and sustainable [6], which has been proven to be one of the most promising solutions. Solar still is a typical solar seawater desalination device involving three processes, including absorbing solar energy, converting it into heat to evaporate seawater, and condensing it into freshwater at a cooler surface, which has been widely studied. Solar stills are mainly powered by solar energy and can be used in areas with abundant solar energy but scarce electricity. Solar still can not only effectively remove organic and inorganic substances with the removal efficiency of up to 90 percent, but also can successfully remove bacteria from the water [7]. Due to its free source and lower operating costs, it has considerable economic advantages over other existing technologies. In the fourth century B.C., Aristotle showed that seawater could be boiled and cooled to be drinkable. Greek navigators used to boil seawater to produce freshwater. Arab alchemists in late 1551 and Nicolo Gage in 1742 used solar desalination systems [8]. Since then, more and more researchers have begun to study the seawater desalination device of solar still.

Many research articles carried out on increasing productivity of solar still in the open literature. Meanwhile, a series of reviews on improving the productivity of solar stills have been reported. For example, A.E. et al. [9] only reviewed ways to improve the horizontal and vertical tubular solar stills by design and found that the total cost of freshwater for tubular solar stills ranged from USD 0.0061 to USD 0.2 per kilogram of water. Mariem et al. [10] only reviewed the different geometrical designs, wick materials, wick arrangements, and heating system of wick solar stills. Swellam et al. [11] only reviewed working methods, thermal analysis, and enhancement methods of tubular solar stills. Arunkumar et al. [12] only reviewed solar stills that produce more than 5 L/m²/d and categorize them. It also discusses the heat transfer mechanism. Hemanth et al. [13] analyzed the design of different inclined solar stills and found that the active inclined solar stills and the hybrid inclined solar stills have higher freshwater productivity. However, there is no clear classification and inclusive review concerned on methods to improve the productivity of solar still in the literature. In comparison to the recently published review, this review is not a review of a kind of solar still or just a review of one of the methods to increase productivity. This study presents a comprehensive presentation on methods to increase the productivity of solar stills by increasing evaporation and condensation. Through several comparisons before and after the improvement of the solar stills, this study shows the improvement of various ways to increase productivity. We also analyze the advantages and disadvantages of various improvement methods and conduct a cost analysis. This study will not only be a useful resource for researchers who are trying to fully understand solar still technology, but a comprehensive understanding of these methods will help the further design of solar still with more productivity, making it a more viable option for desalination applications.

2. Solar Still

Solar still is the equipment or the device which uses the heat of the sun for freshwater from sea water. The principle is similar to the natural water cycle, including evaporation and condensation. Solar stills absorb the solar energy and heat the seawater into steam.

Steam condensate on a cooler surface and then become flowing water due to gravity. In this process, salts and microorganisms are left in salt water, and freshwater is collected. Solar stills are competitive for small-scale seawater desalination in locations with a large amount of solar radiation, and they have advantages of simple operation, simple structure, simple maintenance, and low cost. Solar stills are divided into active and passive according to whether there are fans, pumps, collectors, or others.

2.1. Passive Solar Still

The working principle of passive solar still is simple. The solar still absorbs sunlight, converts the light into heat, and heats the seawater. The water evaporates, condenses into water droplets when it meets the cold glass cover, and falls for collecting through gravity. Since Swedish engineers designed the first solar still to produce freshwater for mining areas in northern Chile in 1872 [14], researchers have studied different structures of solar stills, such as single-slope single-basin (SSSB) solar stills, double-slope double-basin (DSDB) solar stills, stepped multiple basin pyramid (SMBP) solar stills and so on. Due to different structures, there exists little difference in daily productivity, as shown in Table 1. It can be concluded from Table 1 that the productivity of passive solar stills is all low, although with a small difference in different structures.

Table 1. The productivity and advantage of solar stills with different structures.

Type of Solar Still	Productivity	The Advantage Compared with Single Basin Single Slope Solar Still	Ref.
SSSB solar still	3.2 kg/m ² /d	–	[15]
pyramid solar still	3.51 L/m ² /d	Eliminates the shading impact of the sidewall, increases condensing area.	[16]
solar still with a hemispheric top	4.23 kg/m ² /d	Eliminates the shading impact of the sidewall, increases condensing area.	[17]
DSDB solar still	4.75 L/m ² /d	The upper basin absorbs more radiation, and storage heat, the latent heat of the lower basin is absorbed by the upper basin and evaporates water.	[18]
conical solar still	3.38 L/m ² /d	Eliminates the shading impact of the sidewall.	[19]
stepped solar still	4.353 L/m ² /d	Reduce convection and the distance from the cover to water, minimize shadows, and the water layer is thinner.	[20]
tubular solar still	3.83 L/m ² /d	Eliminates the shading impact of the sidewall.	[21]
SMBP solar still	3.52 L/d	Reduce the thermal capacity in the solar still, increase condensing area.	[22]

Passive solar stills with different structures are shown in Figure 1. The solar stills described above generate water by heating the entire water, but in this way, the heating takes place under water and the vapor is generated in the upper of water, resulting in significant heat loss. In recent years, floating solar stills have gradually drawn people's attention. Interfacial heating concentrates solar energy on the air–water interface and selectively heats a small amount of water on the evaporating surface. Compared with the entire water heating method, the interfacial heating method minimizes the heat transfer of the non-evaporative part of a large amount of water in the evaporation process. Ni et al. [23] invented floating type solar still as shown in Figure 2. Its absorption layer is the hydrophilic black fiber, the insulating structure is made from alternating layers of expanded polystyrene foam and white cellulose fabric; it supplies water to the whole device through capillarity. The study found that the white cellulose fabric accounted for 20% and the thermal insulation layer accounted for 80%. The daily productivity of the device is 2.5 L/m²/d, which is enough for one person to drink for one day. Chen et al. [24] proposed a self-floating solar still inspired by plant roots, as shown in Figure 2. The daily productivity is 1.5 kg/m²/d. In sum, the daily output of the two kinds of solar still needs to be further improved.

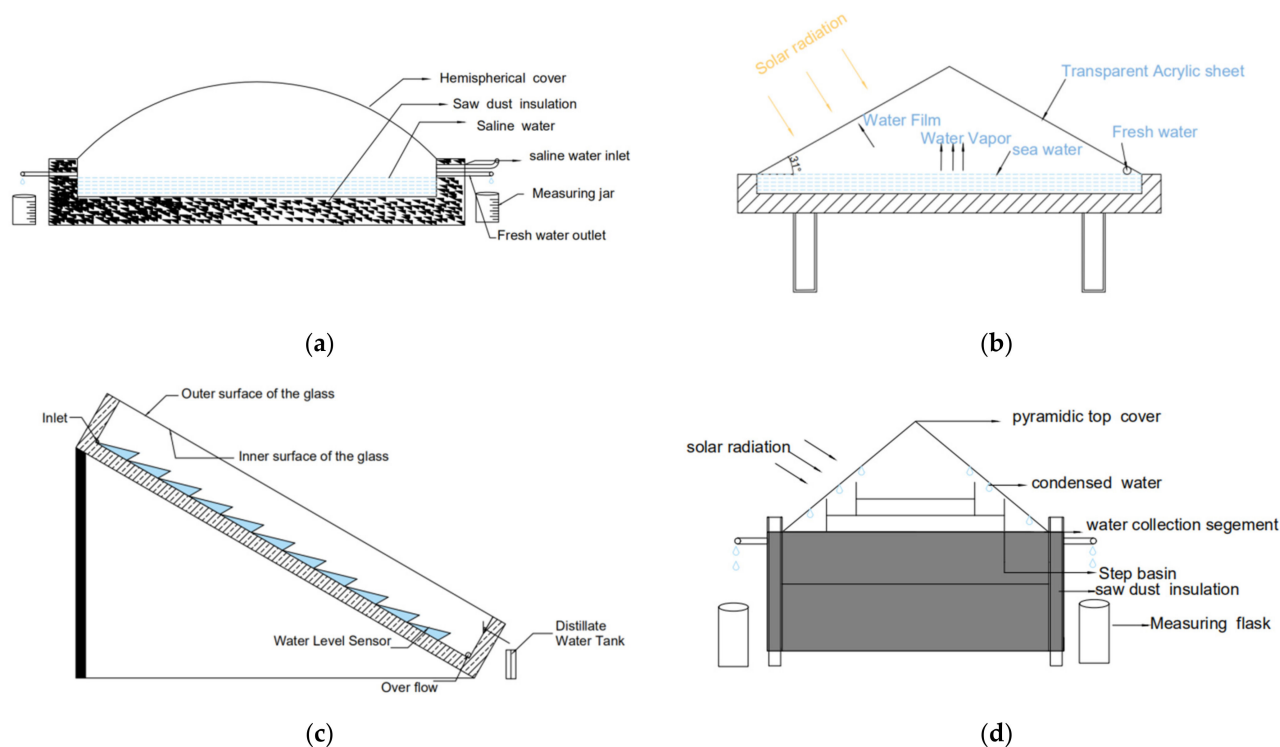


Figure 1. Passive solar still with a different structure adoption from (a) solar still with a hemispheric top reprinted with permission from [17]. Copyright 2012 Arunkumar T, (b) conical solar still reprinted with permission from [19]. Copyright 2015 Gad HE, (c) stepped solar still reprinted with permission from [20]. Copyright 2018 Abujazar MSS, (d) stepped multiple basin pyramid solar still reprinted with permission from [22]. Copyright 2020 Prakash A.

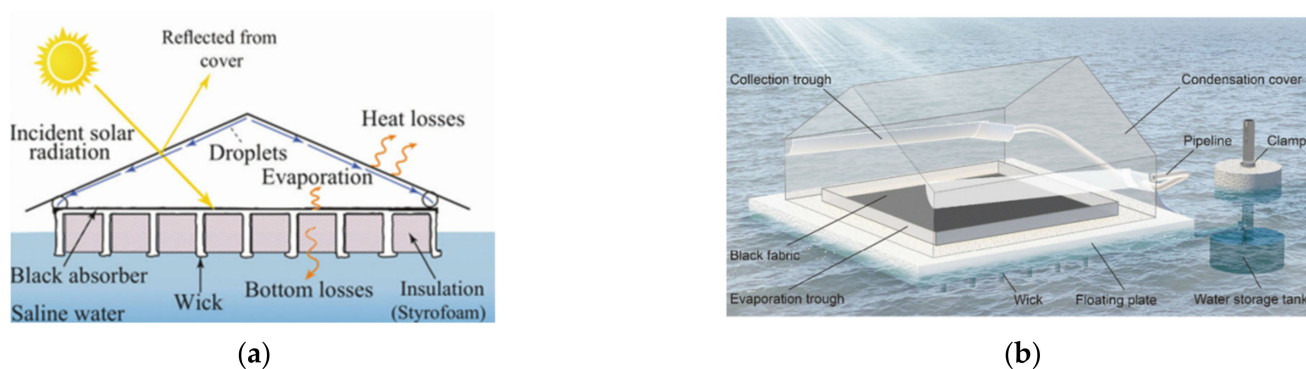


Figure 2. The picture of solar still with interfacial evaporative (a) a floating type solar still reprinted with permission from [23]. Copyright 2018 Ni G, (b) self-floating solar still inspired by plant roots reprinted with permission from [24]. Copyright 2021 Chen S.

2.2. Active Solar Still

Active solar stills have different working principles due to the addition of different auxiliary parts. By adding a collector, the solar still can receive more sunlight. Fans are added to lead steam into separate condensing chambers for condensation and so on. Active solar is still made of an external power source or collector with passive solar still to enhance mass and heat transfer. Omara and Mohamed [25] used a disc collector to concentrate the heat of seawater at the focal point and found that the efficiency of this method was 68% higher than that of traditional solar still. Arunkumar et al. [26] studied compound parabolic collector tubular solar still (CPC-TSS) and compound parabolic concentrator concentric tubular solar still (CPC-CTSS) as shown in Figure 3. The results showed that the daily productivity of CPC-TSS and CPC-CTSS was 3.71 L/d and 4.96 L/d, respectively.

Pounraj [27] put forward a kind of active solar still, which used photovoltaic panels and was coupled with a Peltier heat exchanger, as shown in Figure 2. The seawater was heated by solar energy and the Peltier converted solar photovoltaic panels into electricity, this design produced more steam, and the Peltier heat converter was used to cool the condensing surface, which increased both evaporation and condensation. The experimental results showed that the productivity of the device is about 6.5 times higher than the productivity of the traditional passive solar still. Manokar et al. [28] proposed an inclined solar still with a solar photovoltaic panel, which could generate electricity while producing water. The experimental results showed that the productivity of modified inclined solar still with the insulation layer at the bottom and side reached 7.3 kg/d. Manokar et al. [29] also reviewed solar stills with photovoltaic panels and found daily productivity of this solar still was 6–12 L/m². The productivity comparisons between active solar stills and passive solar stills are listed in Table 2.

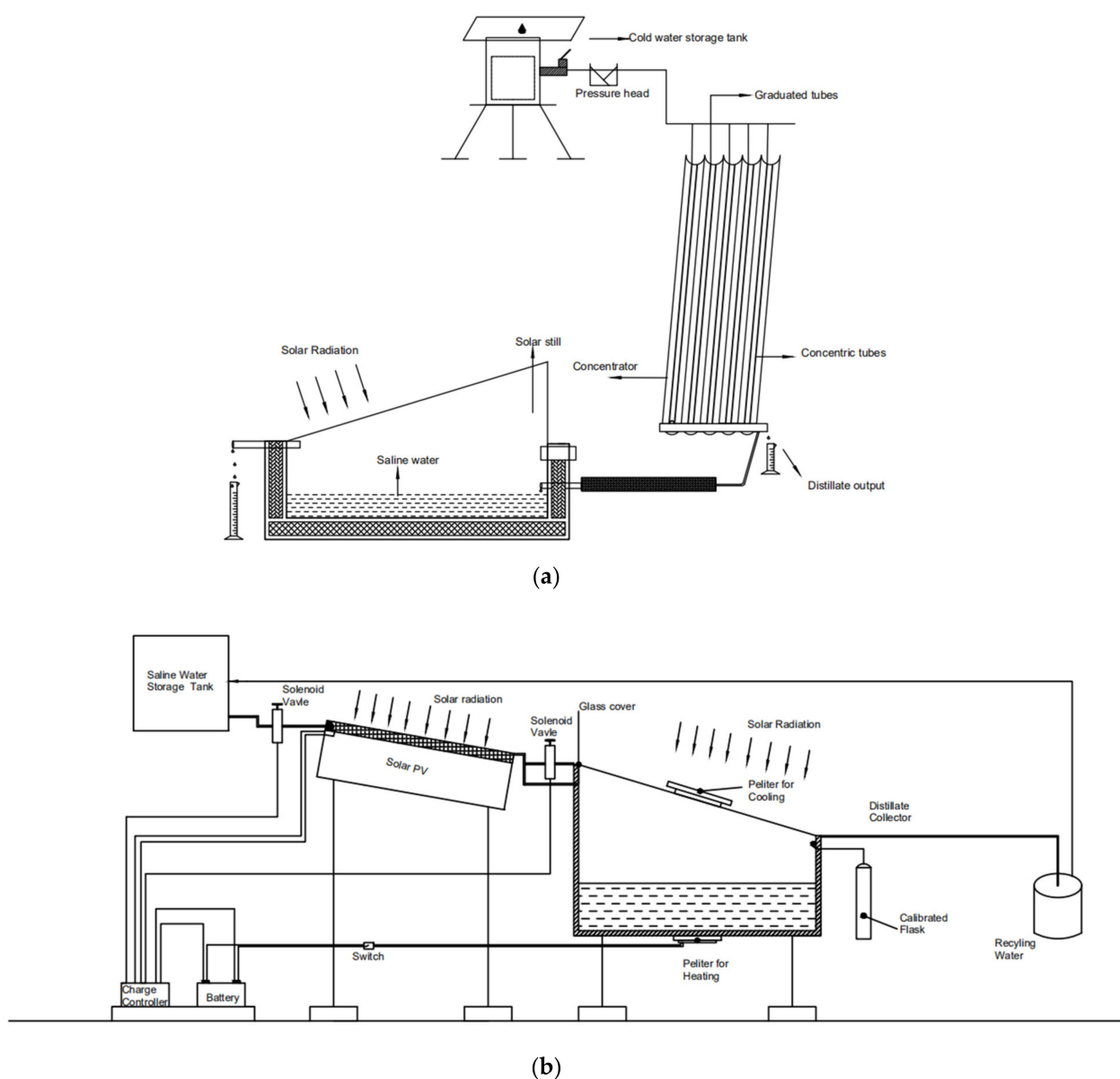


Figure 3. Active solar still adoption from (a) compound parabolic concentrator concentric tubular solar still reprinted with permission from [26]. Copyright 2016 Arunkumar T, (b) solar still with PV and peltier reprinted with permission from [27]. Copyright 2018 Pounraj P.

Table 2. The productivity of active solar stills compared with passive solar stills.

Type of Passive Solar Still	Productivity	Type of Active Solar Still	Productivity	Productivity Increase	Ref.
SSSB solar still	3.4 L/m ² /d	Stepped solar still with solar air heater	6.3 L/m ² /d	112%	[30]
SSSB solar still	3.6 L/m ² /d	Stepped solar still with internal and external reflector	8.1 L/m ² /d	125%	[31]
SSSB solar still	1.66 L/d	Pyramid solar still with flat plate collector	3.1 L/d	60%	[32]
SSSB solar still	2.488 L/d	SSSB solar still with evacuated tubes	5.09 L/d	104.68%	[33]
Multi-side-stepped square pyramid (MSSSP) solar still	13.44 L/m ² /d	MSSSP solar still with a small salt-gradient solar pond	15.18 L/m ² /d	13%	[34]
SSSB solar still	2.4 L/m ² /d	SSSB solar still with PV	2.62 L/m ² /d	10%	[35]

In summary, compared with the passive solar still, the active solar stills do have a certain increase in freshwater productivity. However, the active solar stills also make the desalination devices more complex, and the area is also significantly increased due to collectors and other factors. Some active solar stills require extra electricity, which is not very useful in remote areas with scarce electricity.

2.3. Factors Influencing the Performance of Solar Stills

Some factors affect the productivity of a solar still, including controllable factors such as water depth and cover angle, as well as uncontrollable factors such as solar radiation, wind speed, temperature. The design of solar stills can have a better performance by optimizing controllable factors such as water depth, water mass flow rate, and the angle of the condensing cover.

2.3.1. Controllable Factors

Water depth. Many researchers have found that the productivity of solar stills decreases when the depth of water exceeds a certain level. Tiwari et al. [36] found that when the water depth was 2–10 cm, the productivity of the solar stills decreased as the depth increased. When the light-absorbing plate was at the bottom, the water depth in the solar still was deep, which made it difficult to avoid serious heat loss due to the consequence of the heating area to the water and the environment. And in turn, the amount of steam decreased. Manokar et al. [37] researched the water depth from 1 to 3.5 cm in the pyramid solar stills. The result showed that the productivity was highest at the depth of 1 cm for both insulations.

Cover angle. The productivity of the solar stills depends on the angle of the condensing cover of the solar still. If the angle is too low, a part of droplets will fall into the basin, while if the angle is too high, the reflection of radiation may increase. Kumar [38] found that the performance of the system was optimal when the angle of the condensing glass cover was 15° in a single-slope solar still coupled with a flat-plate collector. Abdul [39] pointed out that the cover angle should be large in winter and small in summer, and the productivity would be better when the cover angle was close to the latitude angle of the location.

Besides the controllable factors mentioned above, some other controllable factors, such as insulation materials and insulation layer thickness, are also important factors affecting the productivity of a solar still. Optimizing these controllable factors can improve the productivity of solar stills.

2.3.2. Uncontrollable Factors

Solar radiation is an important factor that influences the yield of the solar still. When solar radiation is low, the solar energy absorbed by solar still will decrease, resulting in the productivity decrease of freshwater. The research of Rahbar [40] found that the variation trend of daily efficiency and solar intensity was consistent, indicating that the daily productivity was in direct proportion to the solar radiation. The researchers also found that ambient temperatures affected the yield of solar stills, which meant that higher ambient

temperatures could increase the productivity of solar stills. Al-Hinai [41] showed that productivity of the solar still increased by 8.2% when the ambient temperature increased by 10 °C. Wind speed also affects the productivity of solar stills. However, because high wind speed not only reduces the ambient temperature but also decreases the temperature of the condensing cover, the effect of wind speed on the productivity of solar stills is a complex process. Zurigat [42] showed that increasing wind speeds from 0 to 10 m/s increased productivity by more than 50%. Since some factors, such as solar radiation, cannot be controlled, a series of methods are proposed to increase the absorption of solar radiation to increase productivity.

The productivity of a solar still is severely affected by climate, operation, and design parameters. As climatic conditions, such as solar radiation, ambient temperature, and wind speed, are uncontrollable, productivity needs to be optimized by optimizing the operation and design conditions. However, the daily productivity is still low. Because the freshwater produced by solar stills can be divided into evaporation process and condensation process, these searchers improved the daily freshwater productivity of solar stills by increasing the evaporation rate and condensation rate of solar stills.

3. Methods to Increase the Productivity of Solar Stills

The desalination process of solar stills is mainly divided into evaporation and condensation, so the main ways to increase the productivity of solar stills are to increase the efficiency of evaporation and condensation.

3.1. Improvement of Evaporation Efficiency

Generally, there are two main ways to generate vapor in solar still. One is to generate steam by heating the whole water, and the other is to generate vapor by evaporation at the interface. There are ways to increase vapor generation in a solar still by heating the entire water block (i) using energy storage materials; (ii) adding nanoparticles; (iii) changing the structure of the absorption plate; and (iv) using photothermal materials. As shown in Figure 4, interfacial evaporation concentrates solar energy at the air-water interface, heating a small amount of water on the evaporating surface. Interfacial evaporation reduces heat loss compared to heating the entire water. For the interfacial evaporation of solar still, the main way for improving the evaporation rate of solar still is using photothermal materials.

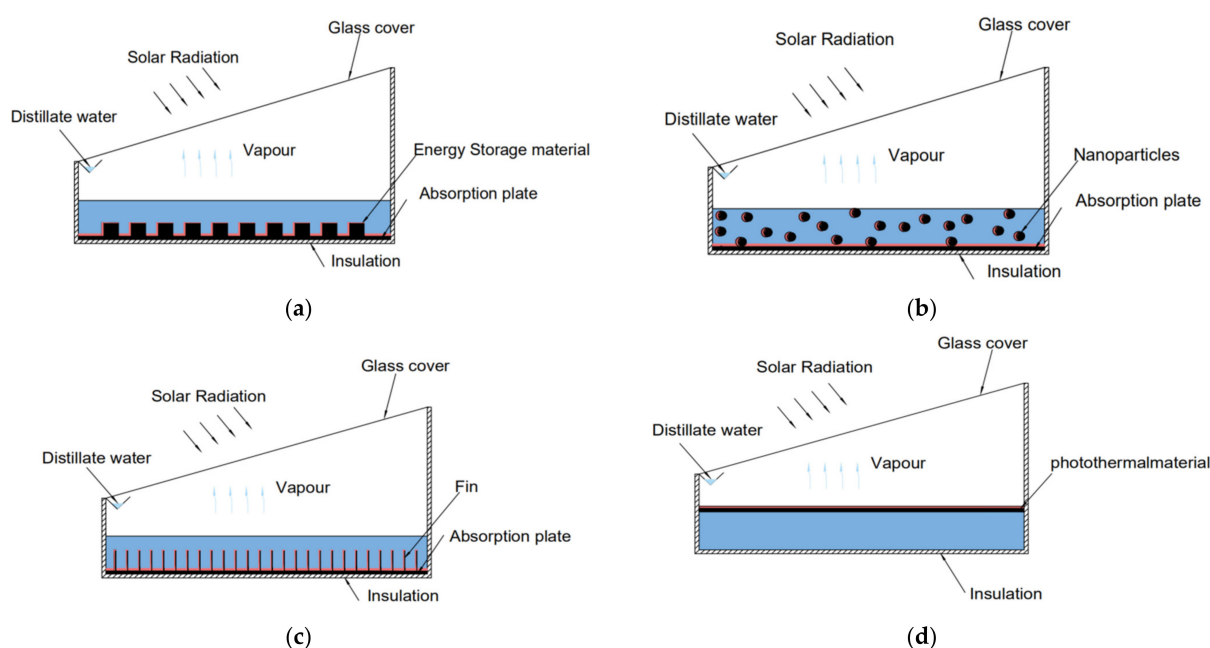


Figure 4. Schematic diagram of methods to increase the productivity of a solar still (a) using energy storage materials, (b) adding nanoparticles, (c) adding fins on the absorption plate, and (d) using photothermal materials.

3.1.1. Using Energy Storage Materials

To improve the productivity efficiency of solar stills, many researchers have studied heat storage materials. Heat storage materials can store a certain amount of heat and release it at night when solar radiation is low. In this way, freshwater productivity increases at night. Heat storage materials are mainly divided into two categories, one is sensible heat storage materials mainly including sand, charcoal, etc., and the other is latent heat storage materials mainly including phase change materials paraffin, fatty acids, inorganic salts, brine mixtures, etc. Sensible heat storage materials rely on the temperature change of heat storage materials to store heat. The exothermic process cannot maintain a constant temperature so that there is a temperature difference with the surrounding environment, which results in heat loss and incapability of heat storage for the long term. Latent heat materials, especially phase change materials, can absorb or release a large amount of latent heat during the process of physical state transformation, and can also change the material state and provide latent heat without changing the temperature. The application of phase change materials (PCM) as latent heat materials in solar still may not increase the total productivity of solar stills. The productivity of freshwater at night increases with the increase of PCM, but the productivity of freshwater during the day is decreased with the increase of PCM [43]. Radhwan [44] found that the productivity of the stepped solar still without PCM was 4.9 L/m²/d but that of the stepped solar still with PCM was 4.6 L/m²/d. Many researchers have added energy storage materials to solar stills to increase productivity. Table 3 lists some examples of solar stills with energy storage materials.

It can be seen from the above and Table 3 that different types of energy storage materials have a slightly different increase in freshwater yield. In this paper, the increased range of freshwater productivity is 0.48–273%. Among them, the output of sponge cube to solar still is extremely high, which can reach 273%. However, salt and rust in saline water would accumulate on sponges, which would reduce capillarity and even emit a bad odor, seriously affecting the quality of condensation water [45]. Therefore, more factors should be considered when selecting energy storage materials in practice.

Table 3. Performances of solar stills with energy storage materials.

Energy Storage Materials	Type of Solar Still	Productivity	Productivity Increase	Ref.
Charcoal	DSDB solar still	4.5 L/m ² /d	125%	[46]
	Rectangular solar still	1.46 L/m ² /d	15%	[47]
Sand	SSSB solar still	3 L/m ² /d	75%	[48]
	SSSB solar still	5.06 L/m ² /d	34.57%	[49]
Black granite gravel	Double basin (DB) solar still with Vacuum collector tube	8 L/m ² /d	65%	[50]
	SSSB solar still	3.9 kg/m ² /d	18%	[51]
	SSSB solar still	3.572 L/m ² /d	9.5%	[52]
Paraffin wax PCM	SSSB solar still of V-shaped absorption plate	3.761 L/m ² /d	12%	[53]
	SSSB solar still coupled with solar air collector	9.36 L/m ² /d	108%	[54]
Sponge	SSSB solar still	2.47 L/m ² /d	0.48%	[43]
	SSSB solar still	—	273%	[55]

3.1.2. Adding Nanoparticles

Nanofluid is the uniform, stable and high thermal conductivity suspension prepared by adding solid particles of nanometer size to the base liquid. Nanoparticles enhance the absorption of light at certain wavelengths by absorbing, scattering, and reflecting the incident light. Nanoparticles improve the thermal conductivity and convective heat transfer coefficient of the fluid by mixing nanoparticles with water, thus increasing the evaporation rate. Modi et al. [56] found that the productivity and efficiency of the solar stills with nanoparticles were higher than those without nanoparticles, but the productivity decreased

with the increase of concentration of Al_2O_3 nanoparticles from 0.01% to 0.2%. In 2008, the review by Yu et al. [57] showed that the current nanofluid heat transfer enhancement was in the range of 15–40%. Some researchers have added nanoparticles to solar stills to suspend the particles in the water, thus increasing their freshwater productivity. Table 4 shows the changes in the productivity of solar stills after adding nanoparticles.

However, the high surface energy of nanoparticles in nanofluids, poor dispersion stability, and easy agglomeration results in increased thermal resistance and serious heat loss in the heat exchange process [58]. Therefore, it is necessary to use new nanofluids with good dispersion and heat conduction properties.

Table 4. Productivity of solar stills with nanoparticles.

Nanoparticles	Type of Solar Still	The Productivity before Adding Nanoparticles		The Productivity after Adding Nanoparticles		Productivity/Productivity Increase	Reference
CuO	SSSB solar still	at the depth of 5 cm	2.814 L/m ² /d	3.445 L/m ² /d		22.4%	[59]
		at the depth of 10 cm	2.351 L/m ² /d	3.058 L/m ² /d		30%	
Al_2O_3	Double slope (DS) solar still	1.2225 L/m ² /d		0.04%	2.665 L/d	8.99%	[60]
				0.08%	2.691 L/d	10.06%	
				0.12%	2.744 L/d	12.23%	
Al_2O_3	SSSB solar still	0.655 L/m ² /d		0.935 L/m ² /d		29.95%	[61]
ZnO				0.75 L/m ² /d		12.67%	
TiO_2				0.805 L/m ² /d		18.63%	
Al_2O_3	DSSB solar still	0.989 L/m ² /d		1.252 L/m ² /d		26.60%	[62]
CuO		1.014 L/m ² /d		1.585 L/m ² /d		56.31%	
Cu_2O	SSSB solar still	2.9 L/m ² /d		4 L/m ² /d		54.54%	[63]
Al_2O_3 -CuO	SSSB solar still	summer	4.392 L/m ² /d	5.5239 L/m ² /d		27.2%	[64]
		winter	2.553 L/m ² /d	3.1079 L/m ² /d		21.7%	

3.1.3. Changing the Structure of the Absorption Plate

Most traditional solar stills take the inner surface of the device as the absorption plate of solar radiation. To effectively absorb solar energy, the inner surface of the device is often painted black. Researchers have proposed various ways to increase solar absorption to increase freshwater productivity, including adding fins and adding suspension boards. The freshwater productivity of solar stills increased by adding fins because fins can transfer heat to water. Samuel et al. [65] studied absorption plates of different shapes, including flat, trough, and fin absorption plates. The results showed that the fin absorption plate improved the efficiency of the system, which was 25.75% higher than that of inclined solar stills. The productivity of freshwater can be influenced by different structures and the different number of fins. Compared with solid fins, hollow fins with a circular and square cross-section not only reduce the quality of the panels but also provide a larger area to improve the productivity of freshwater by increasing absorption of solar radiation and heat transfer from the plates to water. Table 5 summarizes the influences of the different shapes of fins, the number of fins, the thickness of fins, and the material of fins on freshwater productivity.

El-sebaai et al. [66] studied a single-basin single-slope solar still with movable baffle, which divided the basin into upper and lower parts, and transferred the absorbed solar energy to the upper and lower parts. The results showed that daily productivity was 20% higher than that of traditional solar stills. Nafey et al. [67] used models and experiments to study a solar still with a 0.5 mm diameter perforated aluminum plate. They found that the actual experimental result was consistent with the model, and the productivity efficiency of the solar still with black perforated plates was increased by 15%. Panchal et al. [68] added MnO_2 nanoparticles to black chrome paint to increase the freshwater productivity of solar stills. The freshwater productivity of solar still coated by black paint with nanoparticles increased by 19.5% compared with coated by black paint absorption board without nanoparticles. The daily productivity can reach 3.2 L/d. The results show that the presence of nanomaterials increases the heat transfer rate.

The addition of movable baffle or fins in the solar still increases the heat transfer area and therefore the water temperature was increased. However, the increased shadow of the fins also leads to the loss of a part of the solar radiation, and even the amount of solar

radiation gained by the fins is equal to the amount of solar radiation lost by the shadow of the fins, resulting in no significant increase in the productivity [69].

Table 5. Productivity of solar stills with different fins.

Type of Fin	Type of Solar Still	Productivity	Productivity Increase	Ref.
Fins with 4 cm height and 1 mm thickness	SSSB solar still	5.377 L/m ² /d	Productivity increased with the increase of fin height, a decrease of fin thickness, and a number of fins.	[70]
Aluminum fin	SSSB solar still	2.64 L/m ² /d	11.36%	[71]
Pin fins	SSSB solar still		14.53%	[72]
Porous fin	SSSB solar still	7.5 L/m ² /d	In February 56% In May 23%	[73]
Rectangular fins	SSSB solar still	2.91 L/m ² /d	45.5%	[74]
Fins made of different materials	SSSB solar still	5.065 L/m ² /d	The material of fin has little effect on the productivity.	[75]
Pin fin	SSSB solar still	4.872 L/m ² /d	23%	[76]

3.1.4. Using Photothermal Materials

Traditional solar still simply puts a layer of black panels at the bottom of the device to absorb solar energy and converts it into heat for desalination. Due to the serious heat loss involved in heating the whole water block, there exists the problem of low solar-thermal conversion efficiency. These materials not only increase the absorbance, but also improve the evaporation efficiency, and thus improve freshwater productivity. This part of seawater desalination photothermal materials began to be used in solar stills, mainly including carbon-based materials, plasma metal materials, semiconductor materials, and polymer organic materials. These materials have been widely used in seawater desalination due to their high solar energy absorption, conversion efficiency, and low thermal conductivity.

Xu et al. [77] prepared a super hydrophilic photothermal film, anchored polypyrrole shells onto cellulose fiber (PCF) paper, which could float on the seawater of a traditional solar still combined with foam as shown in Figure 5. The experimental results showed that the super hydrophilic photothermal film could make the salt that is accumulated in the process of seawater desalination dissolve into the water again. The utilization of solar energy with this photothermal material could be improved greatly. Xu et al. [78] used pencils and paper to make photothermal material. By comparison, the writing pressure of 4H pencil with 2–3 N was a better choice, which made the material have a higher absorption rate of solar energy. Because the plate would reflect part of solar radiation, a photothermal material was proposed to fold it into a 90° V-shaped shape, and at last, it was found that the solar absorption increased. As shown in Figure 5, after putting this kind of photothermal material on the foam, and then putting it into the traditional solar stills for seawater desalination, the researchers found that the productivity of evaporation with plate photothermal material was 1.101 kg/m²/d. The solar energy utilization rate and water productivity of the photothermal material folded into 90° were improved compared with those of unfolded photothermal material. Wu et al. [79] prepared a photothermal material based on nickel foam and nickel oxide nanostructure. The photothermal conversion efficiency of this material was 95%, and the evaporation efficiency of water could reach 1.41 kg/m²/h, and it also showed better stability, water evaporation rate, and efficiency in Bo Hai seawater. Xu et al. [80] designed a self-floating solar still based on printing paper, which can not only desalinate seawater but also collect salt. The experimental results showed that the evaporation efficiency could reach 80% under 900–1700 W/m² solar light.

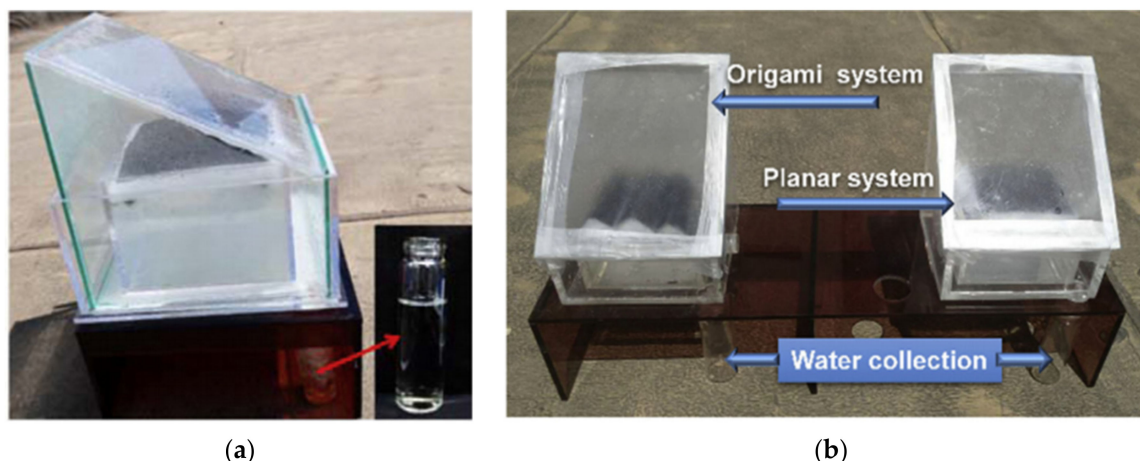


Figure 5. The application of photothermal materials in solar still (a) polypyrrole shell fixed on cellulose fiber paper as a photothermal film in solar still reprinted with permission from [77]. Copyright 2019 Xu Y, (b) photothermal material into 90° V-shaped shape and plate shape in solar still reprinted with permission from [78], Copyright 2019 Xu Y.

Many other photothermal materials were used in solar stills to improve the productivity of vapor, as shown in Table 6. Although this method can improve the evaporation rate of the material, it is easy to cause the problem of salt accumulation. Because of the accumulation of salt on the photothermal material, the absorption of solar radiation will decrease, and the salt will even plug up the steam transport. To solve the problem of salt accumulation, researchers have divided their studies into three main categories: (i) design hydrophobic surfaces; (ii) design hydrophilic surfaces or accelerating the water supply; and (iii) changing the water supply causes salt to build up in the designated place. The principles of these three methods are shown in Figure 6.

Table 6. Productivity of solar stills using photothermal materials.

Photothermal Materials	Type of Solar Still	the Evaporation Rate of Water	Productivity	Salt Accumulation	Ref.
Cotton-CuS Aerogel	SSSB solar still	1.03 kg/m ² /h	—	No salt scale was observed.	[81]
rGo/ MoS ₂ hybrid aerogel	SSSB solar still	0.90 kg/m ² /h	2 L/m ² /d	Virtually free of salt particles.	[82]
beeswax, MCNTs, and PDMS	Pyramid solar still	1.30 kg/m ² /h	—	No salt crystallization on the surface.	[83]
Small-size GO sheets	SSSB solar still	1.73 kg/m ² /h.	9.52 kg/d	—	[84]
Al-Ti-O composite membrane	SSSB solar still	1.24 kg/m ² /h	4 L/m ² /d	—	[85]
Paper-based rGO composite membrane	SSSB solar still	1.778 kg/m ² /h	—	Salts can be redissolved.	[86]
Cu ₂ SnSe ₃ double-layer membrane	SSSB solar still	1.657 kg/m ² /h	—	Salt cannot crystallize on the surface.	[87]
Black gold sponge	SSSBsolar still	1.24 kg/m ² /h	7.4–8.0 kg/m ² /d	No salt crystallization on the surface.	[88]
RGO/cotton fabric	DSSB solar still	1.47 kg/m ² /h	4 L/m ² /d	Salts redissolved quickly in channels.	[89]
Carbonized rice straw composited with bacterial cellulose	SSSB solar still	1.2 kg/m ² /h	4.6–7.9 kg/m ² /d	Salt crystallizes at the edge.	[90]
3D evaporator with CNT	SSSB solar still	2.63 kg/m ² /h	1.72 kg/m ² /h	Salts can be easily removed and collected.	[91]
Graphene PVA hydrogel	SSSB solar still	2.19 kg/m ² /h	13.68 kg/m ² /d	Salt resistance.	[92]
Molybdenum Carbide / Carbon-Based Chitosan Hydrogel	self-designed solar still	1.77 kg/m ² /h	12 L/m ² /d	—	[93]

Although the current laboratory photothermal evaporation has a high evaporation rate, in practical application, due to the light loss of film on the condensation cover and the heat loss in the environment, the freshwater productivity efficiency is far lower than the evaporation efficiency. This can be seen clearly from the comparison of the evaporation rate of seawater with the actual daily freshwater collected in the table below.

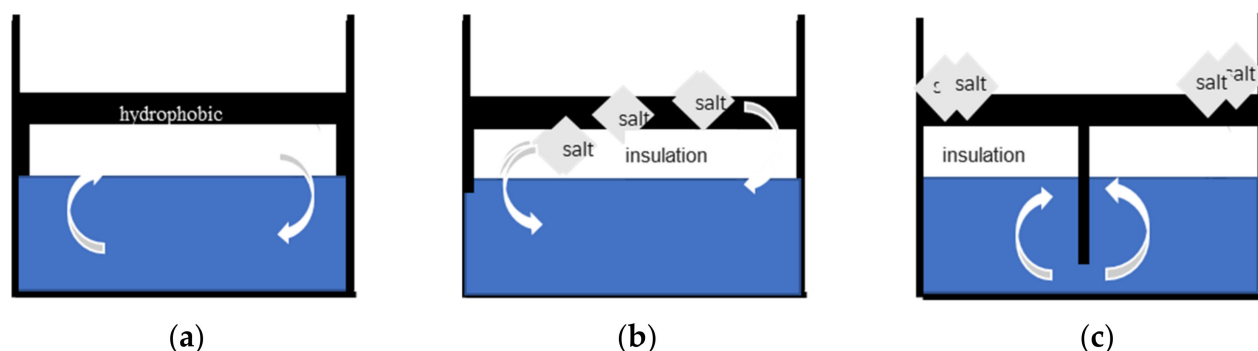


Figure 6. (a) Design hydrophobic surfaces; (b) design hydrophilic surface or accelerating the water supply; and (c) changing the water supply causes salt to build up in the designated place.

All four of these methods can increase the productivity of solar stills, but they also have some disadvantages. Table 7 summarizes the advantages and disadvantages of the four methods.

Table 7. Advantages and disadvantages of the above methods.

Methods	Advantages	Disadvantage
Using energy storage materials	store an amount of heat and release it at night or low solar irradiation	salt and rust in saline water would accumulate on sponges, which would reduce capillarity some phase change materials may affect the water quality poor dispersion stability and easy agglomeration
Adding nanoparticles	enhance the absorption of light at certain wavelengths by absorbing, scattering, and reflecting	increased thermal resistance serious heat loss might be toxic
Changing the structure of the absorption plate	increases the heat transfer area	the increased shadow leads to the loss of a part of the solar radiation
Using photothermal materials	high solar energy absorption conversion efficiency low thermal conductivity	some materials price is high salt accumulation on materials surface

3.2. Improvement of Condensation Efficiency

All of the above methods increase the freshwater productivity of solar stills by increasing the productivity of evaporation. The rate of productivity of freshwater is directly related to the rate of condensation. Due to the constant productivity of steam in solar still, the temperature difference in the solar still will be reduced, resulting in the vapor cannot be condensed. To increase productivity, temperature difference should be maintained as well as increasing the condensation rate of the vapor. The increase of condensation is mainly divided into three methods: (i) cooling the condensation surface, (ii) increasing condensation area, (iii) using a separate condensation chamber, and (iv) changing the wettability of the condensing surface.

3.2.1. Cooling the Condensing Surface

The productivity of solar stills depends on the evaporation rate and the condensation rate. Tiwari and Bapeshwararao [94] found that water flowing across the glass surface increased condensation rates and nearly doubled freshwater productivity. The device was shown in Figure 7. However, as the flow of water on the glass increases, the amount of productivity drops slightly. Through numerical simulation and experimental verification, Lawrence et al. [95] found that the efficiency of the solar still with black dye and water flowing through the glass cover was improved by 7% and 10%, respectively, compared

with solar stills in which there is no water flowing through the glass surface. Due to the large temperature difference between the glass lid and the water mass in the tank, water flowing through the glass surface not only increases the condensation rate but also evaporates rapidly. Tiwari and Sinha [96] designed a kind of active solar still as shown in Figure 7, the solar still coupled with internal heat exchanger and plate solar collector, the cold water flowed to the glass surface and then entered into the solar still. Cold water decreased the temperature of the condenser surface, and thus increased the efficiency of condensation. The water that absorbed the latent heat of evaporation was preheated and then entered the solar still. Abu-Hijleh [97] used a mathematical model to study the effect of productivity of solar still with water film cooling under different conditions. The water film cooling efficiency increased with the increase of light, at 1400 W/m^2 solar radiation, the productivity of the solar still increased by 6%.

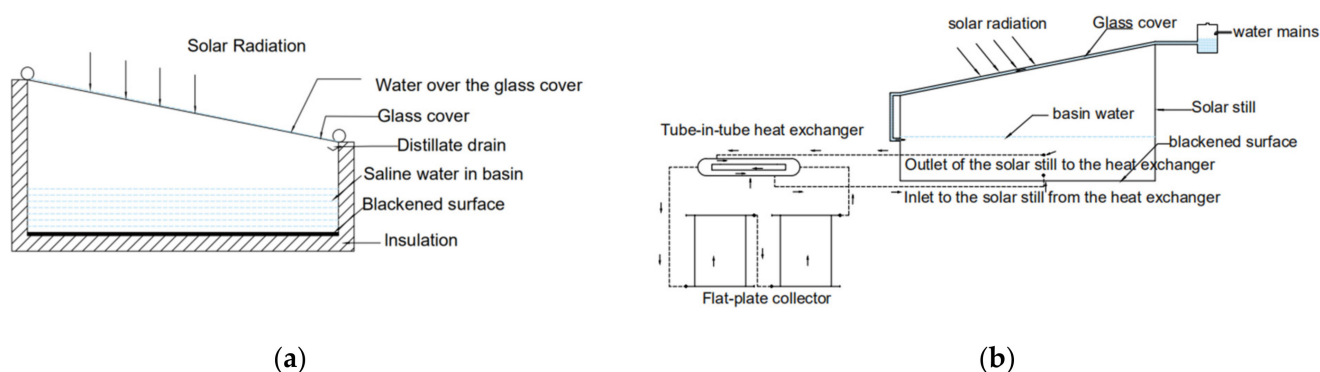


Figure 7. Several diagrams for improving condensation efficiency adoption from (a) schematic of solar still with water flowing over the glass cover reprinted with permission from [94]. Copyright 1984 Tiwari GN, (b) schematic of an active regenerative solar still reprinted with permission from [96]. Copyright 1993 Tiwari GN.

Table 8 shows that the productivity of the solar still increases with cooling the condensation surface. The cooling of the condensation surface increases the temperature difference between the water and the condensation surface and accelerates the productivity of the solar still. In summary, the productivity of solar stills is increased by water cooling or air cooling condensation surface. While water cooling can improve the productivity of solar still with reasonable design, water cooling can reduce the absorption of solar radiation in solar still. The cooling film may offset some of the effects of wind speed on the efficiency of the still.

Table 8. Productivity of solar stills with cooling the condensation surface.

Type of Solar Still	Method of Cooling Cover	Productivity without Cooling the Condensing Surface		Productivity with Cooling the Condensing Surface	Productivity Increase	Ref.
SSSB solar still	air cooling cover	2.805 $\text{L/m}^2/\text{d}$		3.24 $\text{L/m}^2/\text{d}$	15.5%	[98]
	Water cooling cover	3.23 $\text{L/m}^2/\text{d}$		4.259 $\text{L/m}^2/\text{d}$	31.8%	
	Water cooling cover	1.48 $\text{L/m}^2/\text{d}$		2.19 $\text{L/m}^2/\text{d}$	47.6%	
“V”type solar still	Water cooling cover	2.94 L/d		3.541 L/d	20%	[100]
	Water cooling cover	3.3 $\text{L/m}^2/\text{d}$		4.3 $\text{L/m}^2/\text{d}$	30.3%	
	Water and air cooling cover			4.6 $\text{L/m}^2/\text{d}$	39.4%	
Tubular solar still	Air cooling cover	2.05 L/d		3.05 L/d	49%	[102]
Stepped solar still	Water cooling cover	4 $\text{kg/m}^2/\text{d}$		5.58 $\text{kg/m}^2/\text{d}$	39.5%	
Triple basin solar still	Water cooling cover	5 $\text{kg/m}^2/\text{d}$		8.58 $\text{kg/m}^2/\text{d}$	30%	[104]
DBSB solar still	Water cooling cover	passive solar still	1.15 $\text{L/m}^2/\text{d}$	1.33 $\text{L/m}^2/\text{d}$	15.7%	[105]
Tubular solar still	Water cooling cover	active solar still	1.35 $\text{L/m}^2/\text{d}$	1.63 $\text{L/m}^2/\text{d}$	20.7%	
			4.5 $\text{L/m}^2/\text{d}$	5.85 $\text{L/m}^2/\text{d}$	31.4%	[106]

3.2.2. Increasing the Condensation Area

The condensation rate can be increased not only by decreasing the cover surface temperature but also by increasing the surface area for condensation. Bhardwaj et al. [107] used the device as shown in Figure 8 to study the influence of the increase of condensation surface on freshwater productivity. The results showed that the water productivity increased more than five times with the condensation surface area increasing from 0.08 m^2 to 0.52 m^2 . The main reason is that more condensation areas for the steam were provided, the cooling rate increases with the increase of condensation surface. The article published in 2016 by Bhardwaj et al. [108], demonstrated once again that increasing the condensation area could increase daily freshwater productivity. As shown in Figure 8, the efficiency was increased when the condensation increased by 2.2 m^2 .

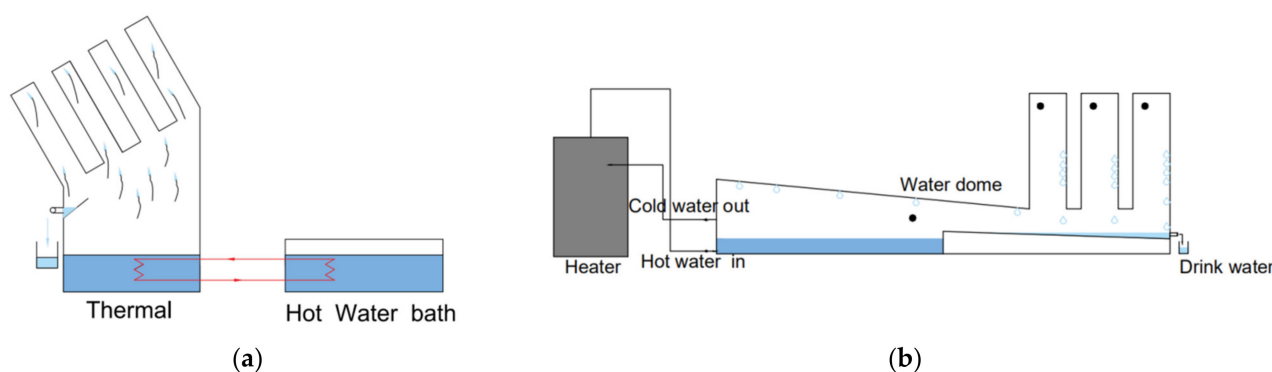


Figure 8. Schematic of solar still with increasing condensing area adoption from (a) solar still with surface increasing from 0.08 m^2 to 0.52 m^2 reprinted with permission from [107]. Copyright 2015 Bhardwaj R, (b) solar still with surface increasing 2.2 m^2 reprinted with permission from [108]. Copyright 2016 Bhardwaj R.

3.2.3. Changing the Wettability of the Condensing Surface

Bhardwaj et al. [109] studied the effect of the condensing surface on the freshwater productivity of the solar still and pointed out that the surface wettability has an important effect on the condensation. The condensation mechanism is film-wise condensation or drop-wise condensation was affected by the wettability of the condensation surface, as shown in Figure 9. Zanganeh et al. [110] showed that silicon nanoparticles coated on Al, glass, brass, cropper, stainless steel, galvanized iron, iron, and PMMA with an inclination angle of 50° reduced the wettability of the condensation surface. The freshwater productivity increased by 24%, 23%, 18%, 27%, 20%, 35%, 44%, and 39%, respectively. Through adding collector, the experiment proved for all inclination angles of condensation surface, drop-wise condensation collects more condensate than film-wise condensation. Zanganeh et al. [111] converted the condensation from a film-wise condensation to a drop-wise condensation by using silicon nanoparticles to reduce the wettability of the condensation surface. It was found that when the inclination angle was 45° , the productivity of condensation on the glass, PET, PMMA, PC, and PVC with silicon nanoparticles were 20%, 26%, 30%, 31%, and 36% higher than that on film-wise condensation, respectively. Khanmohammadi and Khanjani [112] used cold plasma to change the wettability of the condensation surface from film condensation to drop condensation. The experiment found that the freshwater productivity of the solar still increased by 25.7%.

It is well known that the continuous condensing film reduces the heat transfer coefficient, which reduces the water productivity of the solar still. By changing the hydrophilicity and hydrophobicity of the glass cover, the droplet condensation can reduce the thermal resistance and accelerate the movement of the condensate water in the solar still.

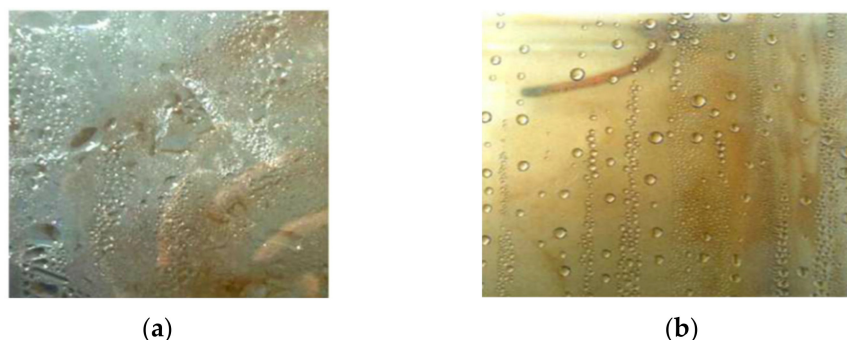


Figure 9. The picture of different condensation mechanisms (a) film-wise condensation and (b) drop-wise condensation reprinted with permission from [110]. Copyright 2019 Zanganeh P.

3.2.4. Using the Separate Condenser

An external condenser allows the hot steam in the solar still to move to the cold surface of the condenser for condensation by diffusion, purge, or natural circulation. The steam can also be drawn into the external condenser by a fan, to increase the condensation amount of steam and then to increase the freshwater productivity of the solar still.

In 1993, Fath [113] proposed to add a condenser to the passive solar still as shown in Figure 10 and carried out a theoretical analysis on diffusion, purge, and natural circulation. Experimental results showed that when the condenser was removed, the total freshwater yield decreased to about 70% of that solar still with the separate condenser. Nikolai et al. [114] proposed a method of using an exhaust fan to discharge steam from a traditional solar still into the separate condenser for condensation. Moreover, the latent heat of condensation was used to preheat the feed seawater. The principle is shown in Figure 10. Tubular solar still with a collector for collecting solar energy was also proposed. The steam passed through a separate condenser. The results showed that the productivity of the first type of external condenser was more than 1 L/m^2 , while that of the traditional type was only 400 mL/m^2 , and the freshwater productivity of the second type of external condenser was 800 mL/m^2 . E-Bahi and Nan [115] presented a new solar still with reflective surfaces and a separate condenser as shown in Figure 10. The result showed that solar still has daily productivity of 4 kg/m^2 . Ravishankar et al. [116] divided the solar still into three parts: evaporation chamber, phase change material preservation chamber, and condensation chamber. Part of the water vapor condensed in the glass cover, and the other vapor condensed in the condensation chamber. El-Samadony et al. [117] proposed stepped solar still with internal and external reflectors, separate condensers, and fans. The experimental results showed that the solar still had a certain increase in productivity efficiency, which was about 66% higher than that of the daily freshwater productivity of the traditional solar still, while the productivity efficiency of using both internal and external reflector and the separate condenser was about 165% higher. Omara et al. [118] compared the traditional solar still with the corrugated solar which had an external condenser and vacuum fan at the bottom. When the water depth was 1 cm, the daily freshwater productivity of the traditional solar still was 2.45 L, while the daily freshwater productivity of the modified solar still was 6.86 L, with a 180% increase in productivity efficiency. Mohaisen et al. [119] studied a solar still with a separate condenser, which is made by galvanizing on the side wall of the solar still. This design improved the condensation rate, the productivity, and efficiency. The daily productivity of solar still was 4.53 kg/m^2 . Rabhi et al. [120] designed a solar still with the external condenser, agitator, and fan as shown in Figure 10. The result showed that the productivity increased by 39.49% because the fan and external condenser enhanced air circulation and vapor condensation. Patel et al. [121] modified a double slope single basin solar still by using an external condenser. They carried out experiments in winter and summer and the results showed that the maximum daily productivity in winter and summer was 8.212 L/d and 11.499 L/d, respectively.

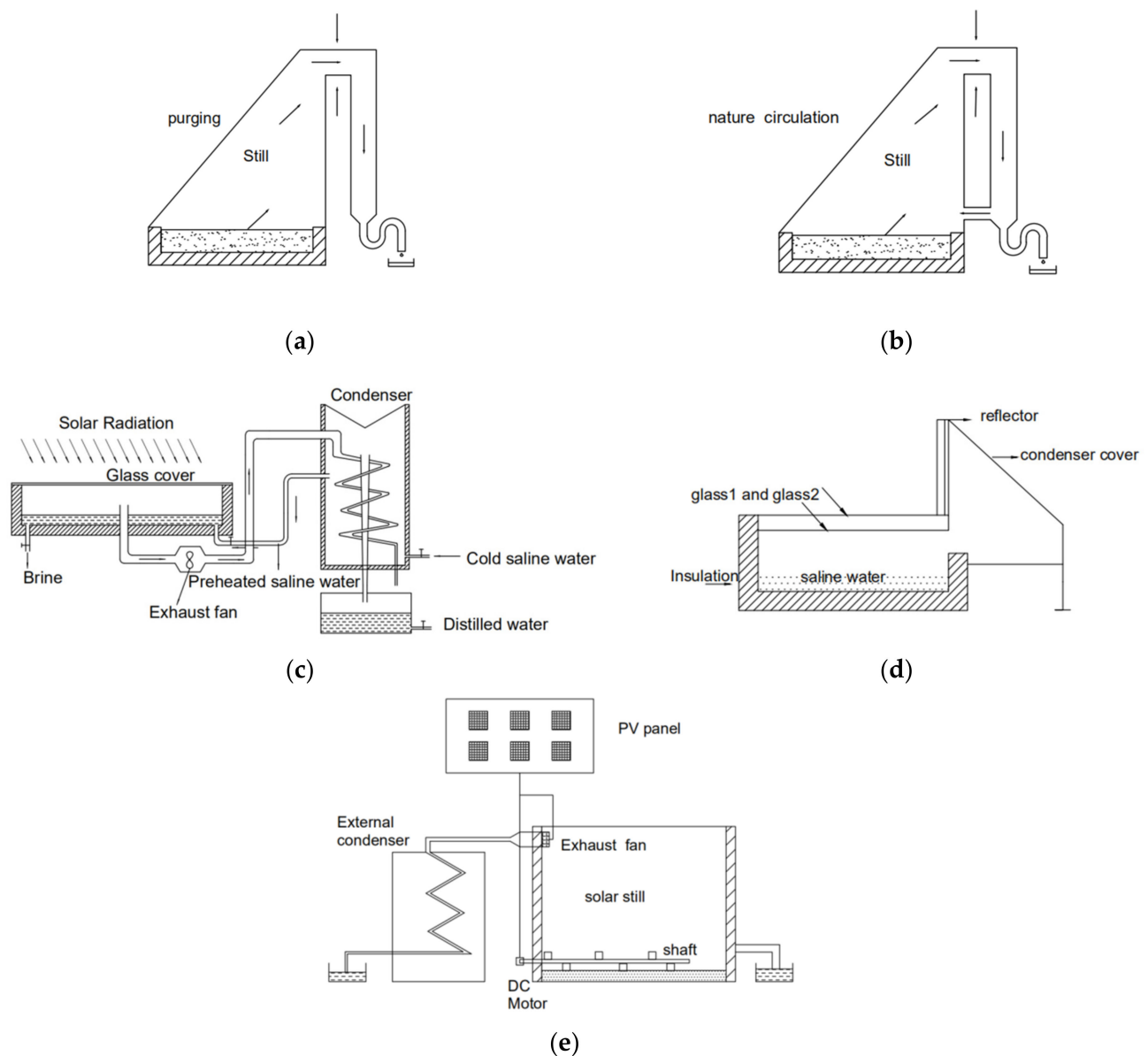


Figure 10. Solar still with a separate condenser adoption from (a) solar still with a separate condenser with purging, (b) solar still with a separate condenser with nature circulation reprinted with permission from [113]. Copyright 1993 Fath HES, (c) solar still with the separate condenser and fan reprinted with permission from [114]. Copyright 1994 Nijegorodov N, (d) solar still with separate condenser and reflector reprinted with permission from [115]. Copyright 1999 El-Bahi A, (e) solar still with the separate condenser, fan, and agitator reprinted with permission from [120]. Copyright 2016 Kumar RA.

Solar stills with separate condensers can increase productivity because of increased condensation rate and reduce the temperature of the glass cover and water basin, an effective way to increase the productivity of solar stills. But electricity consumption by pump and others in forced circulation mode make it more complicated. Table 9 summarizes the advantage and disadvantages of the four methods.

Table 9. Advantages and disadvantages of the above methods.

Methods	Advantages	Disadvantage
Cooling the condensing surface	increases the temperature difference between the water and the condensation surface	reduce the absorption of solar radiation offset some of the effects of wind speed
Increasing the condensation area	increasing the surface area for condensation	solar still takes up more space and becomes more complicated
Changing the wettability of the condensing surface	the higher heat transfer achieved through drop-wise condensation droplets move faster	reduce the absorption of solar radiation
Using the separate condenser	the temperature of the glass cover is greatly reduced glass and basin water temperatures of solar still integrated with the external condenser are less than that of conventional solar still	solar still takes up more space and becomes more complicated electricity consumption by a pump in forced circulation mode

4. Economic Analysis of Solar Still

The cost of solar stills includes investment cost, operation, and maintenance cost. Solar stills have an economic advantage because they require little infrastructure, and they are easy to operate and maintain. The operation and maintenance costs for solar stills are composed of the cost using for filling brackish water, collecting freshwater, cleaning glass covers, removing salt deposits, maintaining the pump and so on [116]. The cost calculation of solar stills is generally based on the following formula.

$$CPL = \frac{AC}{L} \quad (1)$$

$$AC = FAC + AMC - ASV \quad (2)$$

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (3)$$

$$AMC = 0.15FAC \quad (4)$$

$$ASV = S \times SFF \quad (5)$$

$$SFF = \frac{i}{(1+i)^{n-1}} \quad (6)$$

$$FAC = P \times CRF \quad (7)$$

$$S = 0.2P \quad (8)$$

$$\text{Average yield per year/m}^2 = \text{Average daily yield /m}^2 \times 365 \quad (9)$$

where CPL represents the cost of freshwater per liter, AC represents annual cost, L represents annual productivity of solar stills, FAC represents fixed annual cost, AMC represents the annual operating and maintenance costs, ASV represents annual salvage value, CRF represents the capital recovery factor, S represents the salvage value of solar stills, SFF represents sinking fund factor, n represents the number of years of solar still use, i represents the interest rate, P represents the present capital cost of desalination system. Kabeel conducted an economic analysis of 17 different types of solar stills and found that the lowest cost of these 17 solar stills was USD 0.0135/L, and the highest cost was USD 0.23/L [122]. In 2013, a review of the thermo-economic analysis of solar stills by Ranjan and Kaushikde [123] summarized that cost of solar stills at that time was in the range of USD 0.014 to USD 0.237/L. In 2020, Kabeel [9] shown that the average cost of tubular solar still, is ranged between USD 0.0061 and USD 0.02/kg.

Although the productivity of active solar stills will be enhanced, the cost of freshwater might increase with the increase of the investment cost. The cost mainly comes from a series of components of active solar still, such as fans, pumps, solar collectors. Shehata et al. [54] used the above formula to calculate the cost per liter of fresh water for traditional solar stills and improved solar stills with a life of 10 years, it found that the cost per liter of freshwater was USD 0.065/L and USD 0.037/L respectively. Kianifar et al. [124] compared the cost of pyramid solar stills with the cost of pyramid solar stills with a fan. Assuming the price of the fan was USD 10, the result showed that the cost of freshwater per liter for active solar still reduced by about 8–9% compared with passive solar still. Omar [125] compared the cost of a passive double slope single basin solar still with a double slope single basin solar still with a tubular collector, due to the addition of solar collector and pump system, the cost of active solar still was relatively higher. The study showed when the interest rate was 5% and the life was 30 years, the cost was USD 0.018/L and USD 0.036/L, respectively.

The materials of solar still and insulation materials reflect the direct and indirect economy determined in the current studies [126]. As the productivity of solar stills increases, the costs of freshwater per liter also increases. The use of materials, such as energy storage materials, nanofluids, and high-efficiency photothermal materials, should be considered not only for the increase of productivity but also their costs. Yousef [52] used 10 years as a fixed number of years to calculate the cost by using the above formula. Compared with the cost of a traditional solar still, the cost of solar stills with paraffin PCM, solar stills with paraffin wax PCM, and fin and solar stills with water tanks was 0.0427, 0.051, 0.054, and \$0.05/L, respectively. He found the cheapest to be traditional solar still. Shalaby et al. [127] studied that the cost per liter of freshwater for v-type solar stills, V-type solar stills with PCM, solar stills with PCM, and the wick was USD 0.047/L, USD 0.0597/L and USD 0.065/L, respectively, which were lower than the traditional solar stills cost of USD 0.083/L. The floating solar stills mentioned by Ni et al. [15] are expected to last only two years and produce freshwater at USD 1.50/L/m², ignoring all other factors and taking into account the investment cost of material at USD 3/m². Arunkumar [128], by assuming a lifespan of 15 years and the interest rate to be 6%, found that the cost of single slope single basin solar still with carbon impregnated foam and bubble-wrap increased by 62%, but the productivity increased by only 37%. The cost of freshwater per liter was USD 0.0064, while the cost of freshwater per liter of single slope single basin with bubble-wrap was only USD 0.0051. The cost of freshwater per liter is a complicated calculation and cannot be determined by looking at only one aspect of it. There are also many freshwater costs in Table 10.

As mentioned above, the freshwater cost of solar still is about in the range of USD 0.0061–0.277/L, which does not include the use of precious metals and graphene, which are relatively expensive materials, when increasing the productivity of solar still. According to the above and Table 8, we can clarify that the amount of increasing water productivity per day will not necessarily reduce the cost of annual output. It is also an important direction for future research to ensure that the water productivity cost is within a reasonable and acceptable range while greatly increasing the water productivity.

Table 10. The cost comparison of different solar stills.

Type of Passive Solar Still	L (L/Year)	CPL (USD/L)	Reference
SSSB	876	0.0435	[35]
SSSB + PV	956.3	0.052	
SSSB + PV + FAC (forced convection air cooling)	1047.55	0.0493	
CSS + PV as a reflector	952.65	0.0418	
DSSB	766.5	0.0135	[129]
DSSB + fin	839.5	0.0133	
DSSB + fin + PCM + EC + wick	1250.55	0.0177	

Table 10. Cont.

Type of Passive Solar Still	L (L/Year)	CPL (USD/L)	Reference
Solar still with air-condenser	780.7	0.0384	[130]
Solar still with PCM-condenser+ air-condenser	1023.8	0.042	
IASS (inverted absorber solar still)	1569.135	0.0148	[131]
ETC (evacuated tube collectors)	1288.158	0.021245	
ETC + PCM + HP(heat pipe)	1361.158	0.026645	[132]
ETC + EC (external condenser)	2005.675	0.013777	
ETC + PCM + HP + EC	2392.575	0.01527	[133]
SSSB	760	0.0222	
SSSB + PCM	980	0.019	[134]
SSSB + PCM + fin	1100	0.0176	
TCSS	1186.25	0.0348–0.0393	[135]
TCSS + wire mesh	1533	0.0309–0.0347	
SSSB + PTC	1050	0.038	[135]
SSSB + PTC	2182	0.021754	
SSSB + sand	1330	0.021054	[136]
SSSB + PTC + sand	2469.7	0.01937	
SSSB+ Wire mesh	1348.2	0.022554	[136]
SSSB + PTC + Wire mesh	2523.3	0.019913	
SSSB + plated finned heat sink condenser	1263.5	0.023186	[137]
SSSB + plated finned heat sink condenser + PTC	2419.4	0.020308	
SSSB + plated finned heat sink condenser + sand	1462.3	0.020288	[138]
SSSB + plated finned heat sink condenser + PTC + sand	2725.4	0.018164	
SSSB + plated finned heat sink condenser + wire mesh	1348.2	0.022554	[138]
SSSB + plated finned heat sink condenser + PTC + wire mesh	2523.3	0.019913	
SSSB	1168	0.0065	[137]
SSSB + built-in condenser	1569.5	0.0056	
SSSB + built-in condenser + double-layered walls	1799.45	0.0101	[138]
SSSB + PCM + pulsating heat pipe+ built-in condenser	2299.5	0.0093	
SSSB + air-cooled	212.8	0.234	[138]
SSSB + water-cooled	385.5	0.277	
SSSB+ modified water-cooled	468.4	0.201	

5. Challenges and Perspectives

Although the above methods can increase the freshwater productivity of solar stills, there remains problems that prevent some of these methods from being used in real life. (i) It is inevitable to heat the water block by using energy storage materials or adding nanoparticles in the solar still, leading to a large amount of heat loss. Meanwhile, the use of energy storage materials, especially some phase change materials, will affect the water quality and even the health of humans. For example, Harris et al. [45] found that salt and rust in saline water would accumulate on sponges when used as heat storage materials, which would reduce capillarity and even emit bad odor, seriously affecting the quality of condensation water. Anusuih et al. [139] found that although inorganic PCM is well used in heating, it is corrosive. The paraffin phase change material is a commonly used heat storage material, but the paraffin contains benzene, toluene, polyethylene, formaldehyde, etc., which may contain some harmful substances in the steam generated. This situation may harm human health and the environment. Rashidi et al. [140] proposed that freshwater produced by direct contact with nanoparticles in the basin of the solar still might be toxic and might directly affect the health of the operator using nanoparticles. (ii) The problem of salt accumulation in solar stills during seawater desalination is still serious, although some new photothermal materials can avoid salt accumulation; however, these new materials are not suitable for applications, due to the high prices of gold, silver, semiconductor materials, graphene, carbon nanotubes, poor scalability, and stability of some other materials, which are difficult to be applied in practical applications [141]. (iii) To prevent the high temperature of the glass cover from affecting the productivity of solar

stills, some researchers cooled the glass by flowing water across the surface or spraying water on it. Although some heat can be carried away by water, the water on the cover of the glass reduces the absorption of light. (iv) The glass cover of the solar makes it difficult to avoid the formation of water droplets that results in certain refraction of the incident sunlight. Although the solar still let the vapor into the condenser by diffuse, natural circulate, or using a pump or fan, it inevitably forms water on the cover of the glass, so the productivity does not increase by much. Meanwhile, using fans and pumps also increases the operating cost of solar stills.

For future studies on solar still with high productivity, the following are suggested. There is no good application of latent heat of evaporation in solar stills, which leads to a large amount of heat loss. In the future, by optimizing the structure design, the latent heat of evaporation can be used as much as possible to reduce the heat loss and further improve the output of the solar still. Nanoparticles in nanofluids have high surface energy, poor dispersion stability, and are easy agglomeration, resulting in increased thermal resistance and serious heat loss during heat exchange. Therefore, it is necessary to develop new functional fluids with good dispersion and heat conduction properties. Some nanoparticles can be toxic, so the environmental impact of nanoparticles will be considered in the future. Further studies should also be conducted on energy management and economic analysis of nanofluids. In the future, when using fin in solar still, the influence of fin shadow on solar still should be reduced as far as possible, and the most suitable height and thickness should be found in practical application. In the future, we should study new photothermal materials with good economy, scalability and stability that can be used in practical solar stills. Studying the hydrophilicity and hydrophobicity of the material, so that the material will not be too hydrophilic and there is too much water on the material, which increases the heat loss, will be important. Preventing super hydrophobicity caused by insufficient water supply on the surface of the material, to reduce the evaporation rate is also necessary as it can ensure high photothermal conversion efficiency and avoid salt accumulation. Future studies also need to study the balance between water supply and evaporation to prevent excessive water supply from increasing heat loss, to maximize the evaporation rate of photothermal materials. In the future, it is necessary to optimize the cold thickness and speed of water film in the water cooling cover to minimize the influence of water film on solar radiation absorption of solar still to obtain the highest productivity of freshwater. Future studies on changing the hydrophilicity and hydrophobicity of condensing caps should consider the durability, economy, and environmental impact. Hope that portable solar stills, enough for one person to drink, can be designed as soon as possible. Solar stills can be used in emergency treatment, islands, and some remote areas with electricity shortages. In this way, solar stills can move beyond the laboratory and used in real life.

6. Conclusions

It is an urgent problem to improve the yield of freshwater and reduce the cost of producing freshwater in solar still. Therefore, this paper analyzes the factors that affect the productivity of solar distillers and gives a comprehensive review and economic analysis of improving the productivity of solar distillers in two categories: increasing evaporation rate and condensation rate. The productivity of a solar still is severely affected by uncontrollable factors and controllable factors; the productivity needs to be optimized by optimizing the operation and design conditions because the solar radiation, ambient temperature, and wind speed are uncontrollable.

The productivity increases for solar stills using energy storage materials, ranging from 0.48% to 273%. It shows that different energy storage materials have great differences in the increase of solar distiller output. Because of the poor stability of nanoparticles in nanofluids and their easy agglomeration, increasing the productivity of nanoparticles in solar stills is not significant. Because some nanoparticles may be toxic, it is necessary to develop environmentally friendly nanofluids with good dispersion performance and heat transfer. The height and thickness of the fin have an impact on the productivity of solar

still, and the fin material has a smaller effect on the productivity of solar still. Although the photothermal material has a high evaporation rate in laboratory experiments, it has not reached particularly high productivity in the actual application of solar still, which is about 2–13.68 kg/m²/d. The problem of salt accumulation of photothermal materials is remains important. Salt crystallization will cause a drop in absorbance and even block steam escape channels.

The water cooling condensation cover increases the temperature difference between the water and the condensation cover, but it also affects the absorption of solar radiation in the solar distiller due to the formation of the water film. Therefore, reasonable water cooling can increase the productivity of the solar still, otherwise, it will lead to a decrease in productivity. Changing the wettability of the condensing cover makes the solar still form drop condensation, which will improve the productivity of freshwater because of high heat transfer and fasting droplets. Part of the solar still with a separate condenser has a higher output due to auxiliary devices, such as fans and pumps. But these auxiliary devices also make the device more complicated and increase electricity consumption. By comparison, this paper finds that increasing the output of solar still does not necessarily reduce the cost of freshwater. The freshwater cost of solar still is approximately USD 0.0061–0.277/L, which does not include the use of high price materials.

Author Contributions: Conceptualization, investigation and writing-Original draft preparation, H.F.; Supervision and writing-reviewing, M.D.; clarify the logic of the article, H.S.; grammar check and correction, X.H., S.L., K.Y., and M.S.; supervision, writing-reviewing and editing, F.R., I.A., and C.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the fundings of the Key Project of the Joint Fund between the State Fund Committee and Shandong Province (U1806210, U1806212), the Guangdong College Students' Innovative Project (pdjh2021b0538, X201910580158), and the Technology Innovation Project of Zhaoqing (201904030103).

Acknowledgments: This work was supported by the Key Project of the Joint Fund between the State Fund Committee and Shandong Province (U1806210, U1806212), the Guangdong College Students' Innovative Project (pdjh2021b0538, X201910580158), and the Technology Innovation Project of Zhaoqing (201904030103).

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

SSSB	single-slope single-basin
DSDB	double slope double basin
SMDP	stepped multiple basin pyramid
CPC-TSS	compound parabolic collector tubular solar still
CPC-CTSS	compound parabolic concentrator concentric tubular solar still
PCM	phase change material
DB	double basin (DB)
DS	double slope
PCF	polypyrrole shells onto cellulose fiber
FAC	forced convection air cooling
CSS	conventional solar still
PV	Photovoltaic
IASS	inverted absorber solar still
ETC	(evacuated tube collectors)
HP	heat pipe
EC	external condenser

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