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Review Article

Performance Enhancement of Solar Stills with Novel Materials: A Concise Review

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ABSTRACT

According to the severe global warming and increasing demand for freshwater worldwide, different sustainable solutions for supplying water have been considered. Solar desalination is a promising method to convert saline and brackish water resources to distilled water. Solar stills are one of the simple solar desalination methods and have low costs compared to similar solar-powered methods. However, the low distillation capacity and vast distillation area requirements present a challenge for further development of this technique. The application of novel materials that enhance the heat and mass transfer rate in solar stills can be a suitable approach for performance enhancement. In the current review, the most recent advancements according to the novel materials that enhance the distillation rate of the solar stills will be discussed and reviewed concisely. The investigated novel materials in the current review includes different types of natural materials that have been proposed by researchers. Finally, concluding points and future study suggestions will be presented to the researchers. The current review provides the researchers with the most recent advances in the integration of novel materials with conventional solar stills for heat and mass transfer enhancement.

1. Introduction

Freshwater supply has been a severe issue worldwide, and solar desalination can be a promising solution to tackle the water shortage challenge [1, 2]. Solar stills are the most straightforward approach that can be used for low freshwater capacity and remote applications [3, 4]. A solar still consists of a basin and a glass cover works like the water cycle in nature [5, 6]. The water evaporates due to the incident solar radiation. The generated vapor rises and make contact with the lower-temperature glass cover, where the water vapor condensates into the form of freshwater. Finally, the generated freshwater is collected from the down part of glass cover [7, 8]. Low capital and distillation costs, simple construction and maintenance, and portable structure are the advantages of solar stills. Conversely, low distillation capacity, large area requirement, low productivity, and efficiency are the drawbacks of solar stills [9, 10]. The mechanism of heat and mass transfer in the solar stills is based on the convection currents between the glass cover and the saline water, and these currents happen due to the temperature and density difference between the air-vapor mixture over the saline water and under the glass cover. The density difference makes the upward movement of the mixture reach the cooling glass cover and condensates its moisture contents. Low thermal conduction and diffusion affect the majority of air mass not to take part in the process. It should be mentioned that the air-

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vapor mixture intensity's circulation is highly dependent on the difference in the temperature of the saline water and glass cover [10]. There are several approaches proposed for the performance enhancement of solar stills. The application of novel materials in solar stills is the preferred research topic, and researchers have conducted numerous studies in this field. Dyed flax fibers by Abdelgaied et al. [11], waste bottles by Elashmawy et al. [12], natural cellulose fiber by Nguyen et al. [13], graphitized carbon-coated glass fiber cloth by Li et al. [14], graphene oxide composite fiber by Li et al. [15], ultra-robust carbon fibers by Li et al. [16], blended-fiber-based by Liu et al. [17], palm fibers by Miloudi et al. [18], reinforced plastic fiber by Sharon et al. [19], bamboo fiber by Sun et al. [20], carbon-fiber fabric by Tong and Song [21], hollow fibers arrays by Wang et al. [22], date palm fiber by Yadav and Prakash [23], ceramic fiber-based carbon-carbon composite by Yin et al. [24], fiber-based sandwich by Zheng et al. [25], and acetate fibers by Zhou et al. [26] were the examples of the applications of novel materials in solar stills. Moreover, several review articles can be found in the literature considering different aspects of solar stills and methods for their performance enhancement. Shoeibi et al. [27] reviewed the applications of heat pipes and pulsating heat pipes to enhance the performance of solar stills. They concluded that solar stills with heat pipe evacuated tubes have the lowest distillation cost, and solar stills integrated with thermosyphon heat pipes have the highest productivity enhancement. Bait [28] conducted a review study on the effect of novel design concepts including spherical, hemispherical, weir-type, and triangular pyramid on the performance enhancement of solar stills. Based on his review, hemishrical design and weir-type designs have the most water production rate in the literature. Hammoodi et al. [29] reviewed the effective parameters for the pyramid solar stills' performance. Based on their review, operating, design, and environmental parameters can effectively affect the solar stills' productivity. Shoeibi et al. [30] performed a review survey on the enhancement of evaporation and condensation rates in solar stills. They concluded that solar stills with photovoltaic-thermal and glass-cover cooling have the highest water productivity among other techniques. Mohsenzadeh et al. [31] reviewed different innovative designs for improving the performance of solar stills. Their investigation focused on remote-area applications, and they reported the most efficient design for productivity improvement. Dubey et al. [32] conducted a review study on the different designs of dual-slope solar stills and their effects on their performance. Based on this review, the integration of solar stills with phase-change materials and nanoparticles has been proposed for improving their performance. Angappan et al. [33] reviewed different performance enhancement techniques for pyramid solar stills. They reported various techniques, including utilizing phase change materials, fins application, and integrating solar stills with solar thermal collectors. Elsheikh et al. [34] conducted a review investigation on methods for improving the performance of solar stills. They presented several techniques for this purpose, such as forced vibration, heating and cooling techniques, and condensers and reflectors integration with solar stills. Abbaspour et al. [35] reviewed different techniques for enhancing the performance of vertical solar stills. Some of their investigated techniques were dimension optimization of the vertical solar still and utilization of high-absorption materials in the distiller. Abdullah et al. [36] reviewed different performance enhancement techniques for tubular solar stills. They considered methods based on parameters such as geometrical dimensions, condensation rate, and the absorption coefficient of the solar still’s materials. Elgendi et al. [37] reviewed the applications of thermoelectric utilization for improving solar stills' performance. They investigated the thermoelectric cooling, heating, and generator effects and their impacts on the distillation rate of solar stills. Abdullah et al. [38] conducted a review survey on the effect of turbulence generation on the solar still’s performance enhancement. They investigated various turbulence-generating techniques, such as rotating components, ultrasonic fogging utility, vibration generators, and spraying devices. Peng et al. [39] reviewed the applications of nanoparticles and porous media in enhancing the performance of solar stills. They investigated various parameters' effects on productivity, such as nanoparticle concentration, porous material type, and system geometry. Abdullah et al. [40] reviewed the methods for maintaining the minimum basin water depth of solar stills to enhance performance. Some of their investigated techniques are wicks, absorber geometry, and rotating components. Katekar and Deshmukh [41] reviewed the applications of phase change materials effects on the performance enhancement of the solar stills. They concluded that copper oxide nanoparticles are the best material for productivity enhancement of the solar stills found in the literature. Also, several other reviews can be found in the literature about performance enhancement of the solar stills [42], using auxiliary components in solar stills for productivity improvement [43], low-temperature solar stills [44], and approaches for freshwater production rate increase of the solar stills [45].

Previous researchers considered and studied different approaches for the performance enhancement of solar stills. However, the previous reviews rarely investigated the novel natural materials that can enhance the heat and mass transfer of conventional solar stills and consequently improve the distillation capacity of solar distillers. Hence, the current review will investigate the application of most recent innovative materials in solar stills for the heat and mass improvement of the conventional solar stills.

2. Solar Stills Integrated with Novel Materials

This section will explore the previous studies conducted on the applications of novel materials for performance enhancement of solar stills. Agrawal and Singh [46] studied experimentally a solar still with the application of phase change materials. They used novel material of steel wool fiber in the solar still in the form of a mixture with palmitic acid and stearic acid eutectic phase change material. They reported a maximum distillation capacity of 3.4 kg/m^2 and average energy and exergy efficiencies of 38.14% and 11.8%, respectively, with their proposed novel energy storage mixture. Pandey and Gupta [47] experimentally investigated the application of solid clay pots as energy storage for the pyramid solar still. They studied two scenarios of 16 and 36 clay pots in two configurations. They concluded that the mentioned configurations can enhance productivity by 73% and 40%, respectively. They reported a maximum daily water production of 2.19 L/m^2.

Alshqirate et al. [48] worked on an experimental study on the application of natural fibers for pyramid solar still performance enhancement as shown in Fig. 1. They utilized palmately leaf as the natural fiber and inserted the novel material in the solar still's basin for evaporation rate enhancement and distillation capacity increase. They reported 5160.8 g/m^2 for the maximum freshwater production and thermal and exergy efficiencies of 44.9% and 3.4% for their investigated distiller. Finally, they declared a 44.5% productivity improvement with natural fiber. They also determined 0.081 $/L as the water distillation cost.

Fig. 1. Application of palmately leaf as the natural fiber in solar still's basin proposed by Alshqirate et al. [48]

Arunkumar et al. [49] studied experimentally the peanut shell application in solar stills for performance enhancement. They carbonized the peanut shells and coated polyvinyl alcohol sponges for solar still applications. They reported an evaporation rate of 2.16 kg/m^2.h along with 90.4% efficiency. Finally, they showed the potential of peanut shells in the performance enhancement of solar distillers. Dumka et al. [50] experimentally investigated the application of a cotton cloth to enhance the performance of a solar still. Their proposed novel material worked like a tent to prevent extra misting of the still, which enhanced productivity. They reported 53.12% distillation enhancement and 27.46% cost reduction. Also, they reported a thermal efficiency improvement of 44.64% with freshwater production capacity of 307.25 mL/h. Ebrahimpour and Shafii [51] worked experimentally on improving the performance of solar stills with a novel bio mixture of coffee, madder, tea, and dark walnut hull, as shown in Fig. 2. They utilized this novel mixture to increase solar radiation heat gain and consequently productivity. They reported a daily thermal efficiency of 44.2% and a distillation cost of 0.0107 $/L. Their daily distillation capacity was also determined to be 4000 mL/m^2.

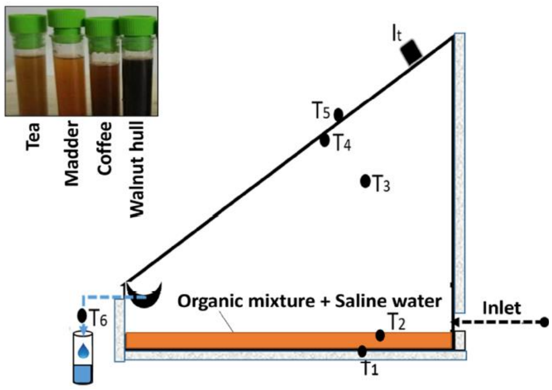

Fig. 2. Application of a novel mixture in solar still's basin proposed by Ebrahimpour and Shafii [51]

Hu et al. [52] worked experimentally on a novel solar still and evaporator using yolk shell material. They utilized a special coating made of a silicone sponge and carbon nanotubes. They reported the enhancement of solar still by their applied coating and reported a 1.72 $kg/m^2.h$ evaporation rate. They also determined the distillation capacity of their proposed solar still to be 11.8 kg/m^2. Kemerchou et al. [53] investigated experimentally solar still performance enhancement by the application of palm stems. They studied the effect of the number of stems on the increase in distillation capacity. They reported the maximum freshwater production of 5080 mL/day for the nine stems scenario. Moreover, they determined a 53.01% improvement rate with thermal efficiency of 57.90% for the mentioned test scenario. Kiriarachchi et al. [54] studied experimentally the application of cotton nanocomposite fibers to enhance the performance of a solar still. Their utilized novel material was plasmonic functionalized cotton nanocomposite fiber integrated with Au and Ag nanoparticles. They reported their proposed water distiller's maximum evaporation rate of 11.3 $kg/m^2.h$ and thermal efficiency of 94.3%. Li et al. [15] worked experimentally on the solar still performance improvement by the graphene oxide composite fiber. Their utilized material was made of non-woven fabric. Based on their results, the application of the mentioned novel materials resulted in 1.54 $kg/m^2.h$ with 97.83% evaporation efficiency. Also, they reported 1.1 $kg/m^2.h$ of average evaporation using their proposed novel fabric. Lu et al. [55] experimentally investigated the application of plant fibers to improve the performance of solar stills. Their novel material was papermaking pulp. They reported an evaporation rate of 1.38 $kg/m^2.h$ with 84.27% thermal efficiency. Finally, they determined 1.75 $\$/m^2$ for their proposed solar distiller capital cost. Mandev et al. [56] studied experimentally the application of cellulose-based absorbent material for the performance enhancement of solar stills as shown in Fig. 3. Their utilized material was used as a water absorber in the basin. They resulted in a 120 g/h water distillation capacity. They also reported 45% thermal efficiency enhancement and 35% freshwater production cost reduction for their proposed water distiller.

Fig. 3. Application of cellulose-based absorbent material in solar still's basin proposed by Mandev et al. [56]

Modi et al. [57, 58] investigated the application of jute cloth as a wick in the double basin solar still performance enhancement. They investigated the effect of heat transfer and the porosity of the novel material on the solar still's performance. They concluded that the application of jute cloth significantly improved productivity and thermal efficiency by 27.31% and 29.37%, respectively. They determined the distillation rate of 942.25 mL/m^2 for their proposed system. Nair et al. [59] studied experimentally the application of chlorophyll pigment and conch shell in the solar still performance enhancement. They reported the maximum freshwater production of 1.2 L/h with 73◦ temperature of the shell. They concluded that 60% productivity can be achieved by applying novel material. Finally, they determined their proposed system's payback period of 2 months. Negi et al. [60] experimentally investigated the application of the Khes novel material as a wick to enhance the performance of solar stills. They concluded that their proposed system can achieve a maximum productivity of 4.372 kg/m2. They also reported a payback period of 1.11 years and a distillation cost of 1.38 ₹/L for their proposed system. Noman et al. [61, 62] studied experimentally the application of pistachio shell powder for tubular solar still performance improvement, as shown in Fig. 4. They showed that this novel material serves as a thermal energy storage and enhanced productivity by 46.26%. They also reported energy and exergy efficiencies of 22.36% and 1.98%, and a payback period of 0.636 years, and 2.7 kg/day of water distillation.

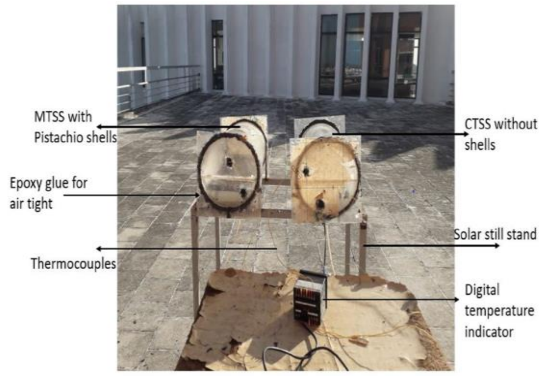

Fig. 4. Application of pistachio shell powder material in solar still proposed by Noman et al. [61, 62]

Sampathkumar and Natarajan [63, 64] experimentally investigated the application of agar-agar fiber to enhance the performance of solar stills, as shown in Fig. 5. Their utilized material was Eucheuma fiber. They reported 22.06% productivity enhancement. They determined the distillation capacity of 3800 mL/m^2.day and 13% thermal efficiency enhancement. Finally, they reported 5.1 months for a payback period with 0.026 $/L freshwater production cost.

Fig. 5. Application of agar-agar fiber in solar still's basin proposed by Sampathkumar and Natarajan [63, 64]

Sibagariang et al. [65] studied experimentally the application of oil palm shells to enhance the performance of a double-slope solar still, as shown in Fig.6. This novel material was used as a heat storage material for the solar distiller. They reported a productivity enhancement of 39% with 2.082 L/m2.day distillation capacity. They also determined 41.71%, 2.994%, and 0.043 $/L.m2 for their investigated system's energy, exergy, and distillation costs.

Fig. 6. Application of oil palm shells material in solar still proposed by Sibagariang et al. [65]

Suraparaju et al. [66-70] investigated experimentally the application of natural fiber on the performance enhancement of solar still. Ridge gourd was their natural fiber as shown in Fig. 7. They determined the distillation capacity of 1600 mL/day for their proposed system. They also reported 4.7 months for payback period and 0.034 $/L for distillation cost.

Fig. 7. Application of Ridge gourd material in solar still's basin proposed by Suraparaju et al. [66-70]

Xiong et al. [71] investigated experimentally the application of polypyrrole-decorated polyester fiber for performance enhancement of the solar stills. They concluded that the evaporation rate can reach 3.77 $kg/m^2.h$. They also reported 26 kg/day freshwater production capacity for their proposed desalination system. Phase change materials (PCMs) applications on the thermal performance enhancement of the solar stills can be considered as one of the possible approaches for the utilization novel materials on the solar stills' freshwater rate increase. Several studies on the PCMs applications such as the utilization of different oil types and paraffin wax [72-76], and biomaterial [77] can be found in literature. The applications of novel porous materials can be also considered as an effective way for solar stills' performance enhancement. Different porous materials such as snail shell biomaterials [78], machining metal scrap [79], waste tyre pieces [80], crushed granite stone [81], black sponge rubber [82, 83] have been proposed by the researchers for solar stills' performance enhancement. Moreover, the application of natural materials on the performance enhancement of solar stills can be found in the literature. These materials such as molasses powder [84], gravel [85], and chrysopogon zizanioides [86] have shown good potentials on the performance improvement of the solar stills. The summary of the different novel materials applications for solar stills performance enhancement is tabulated in Table 1.

Table 1. Different novel materials for performance enhancement of solar stills

Authors	Investigated material	Freshwater production capacity	Main Results
Agrawal and Singh [46]	Steel wool fiber	3.8 kg/m^2	Performance improvement by phase change material integration with novel material average energy and exergy efficiencies of 38.14% and 11.8%,
Pandey and Gupta [47]	Solid clay pots	2.19 L/m^2.day	Productivity improvement of 73% and 40%, respectively for 16 and 36 clay pots
Alshqirate et al. [48]	Palmately leaf as the natural fiber	5160.8 g/m^2	Productivity improvement of 44.5% Thermal and exergy efficiencies of 44.9% and 3.4% The water distillation cost of 0.081 $/L
Arunkumar et al. [49]	Peanut shells	2.16 kg/m^2.h	Evaporation efficiency of 90.4%
Dumka et al. [50]	Cotton cloth	307.25 mL/h	53.12% distillation enhancement 27.46% cost reduction. Thermal efficiency improvement of 44.64%
Ebrahimpour and Shafii [51]	Mixture of coffee, madder, tea, and dark walnut hull	4000 mL/m^2	Daily thermal efficiency of 44.2% and Distillation cost of 0.0107 $/L
Hu et al. [52]	Yolk shell	11.8 kg/m^2	Evaporation rate of 1.72 kg/m^2.h
Kemerchou et al. [53]	Palm stems	5080 mL/day	53.01% distilltion improvement rate Maximum thermal efficiency of 57.90%
Kiriarachchi et al. [54]	Cotton nanocomposite fibers	11.3 kg/m^2.h	Maximum thermal efficiency of 94.3%
Li et al. [15]	Graphene oxide composite fiber	1.54 kg/m^2.h	97.83% of thermal efficiency
Lu et al. [55]	Compressible plant fibers	1.38 kg/m^2.h	Thermal efficiency of 84.27% Capital cost of 1.75 $\$/m^2$
Mandev et al. [56]	Cellulose-based water absorber	120 g/h	45% thermal efficiency enhancement 35% freshwater production cost reduction
Modi et al. [57, 58]	Jute cloth	942.25 mL/m^2	Productivity increase of 27.31% Thermal efficiency increase of 29.37%
Nair et al. [59]	Chlorophyll pigment and conch shell	1.2 L/h	60% productivity enhancement Payback period of 2 months
Negi et al. [60]	Khes wick	4.372 kg/m^2	Payback period of 1.11 years Distillation cost of 1.38 ₹/L
Noman et al. [61, 62]	Pistachio shell powder	2.7 kg/day	Energy and exergy efficiencies of 22.36% and 1.98%, Payback period of 0.636 years

Sampathkumar and Natarajan [63, 64]	Agar/Agar	3800 mL/m^2.day	22.06% productivity enhancement 13% thermal efficiency enhancement 5.1 months for a payback period with 0.026 $/L freshwater production cost
Sibagariang et al. [65]	Oil palm shells	2.082 L/m^2.day	Productivity enhancement of 39% 41.71%, 2.994%, and 0.043 $/L.m^2 for their investigated system's energy, exergy, and distillation costs
Suraparaju et al. [66-70]	Natural fiber	1600 mL/day	Payback period of 4.7 months Distillation cost of 0.034 $/L
Xiong et al. [71]	Polypyrrole decorated polyester fiber	3.77 kg/m^2.h	Evaporation rate of 3.77 kg/m^2.h

3. Conclusions and Future Works

The focus of this review article was on the performance enhancement of solar stills by using novel materials. Various innovative materials were introduced and investigated in this article. Different functions of these materials can be noticed, such as thermal storage effects, increasing heat and mass transfer area, creating a porous medium in the basin, and functioning as a water absorbent. The other point that should be mentioned is the researchers' interest in introducing waste and biomass materials as additive materials to the solar stills to reduce the distillation cost, preserve the environment, and increase the productivity of conventional solar stills. Also, the applications of the PCMs, porous media-based materials and natural materials were considered in the current review. The current research trend in this field shows that in the future, researchers will work more on hybrid biomass-based materials and conduct more experimental studies for further development of solar distillers. Moreover, the synthesis of more novel materials as means of thermal properties improvement, such as thermal conductivity for heat transfer increase of solar stills, is another approach for future studies. The materials with porous structure or with phase change and energy storage characteristics will be more studied in the future for the heat and mass transfer enhancement of the solar stills. Accessibility of the introduced materials is another issue that the researchers should consider. Tecno-economic analysis is also suggested to researchers for the application of novel materials in solar stills to determine the further development potential of the solar stills with innovative materials.

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Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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