Renewable and Sustainable Energy Reviews 186 (2023) 113663

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Application of advanced energy storage materials in direct solar desalination: A state of art review

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ARTICLE INFO

Keywords:
Solar still
Nanomaterials
Phase change materials
Porous materials
Heat pipes
Direct solar desalination

ABSTRACT

Storage of the thermal energy of solar intensity has a significant effect on the efficiency of desalination systems at nighttime, when solar intensity is not available. Solar energy provides the potential to facilitate the freshwater needs of small communities, where access to potable water is commonly limited. However, freshwater generation formation via solar stills remains low when compared to other desalination methods. Hence, multiple innovative materials for efficient water production by solar stills have been invetsigated in the literature, where this is addressed on a wide scale in this comprehensive review. This includes a focus on innovative materials including nanomaterials, nanofluids, nanoparticles-based phase change materials (PCMs), composite PCMs, PCMs with porous materials and PCMs with heat pipes. The review's outcomes identify that advanced energy storage materials substantially influence the enhancement of solar still productivity as compared to conventional solar stills. The results indicate that the application of thermosyphon heat pipes with PCM more than doubles the performance of solar still water productivity. The productivity of solar desalination can also be improved by utilizing PCM/porous materials, with results indicating solar still water productivity to be enhanced by between 40 and 70%. A cost analysis as well as an environmental evaluation of PCM-based solar desalination is also compiled in this review. A summary of the current status, leading groups, journals, and countries related to advanced energy storage materials in solar desalination is presented. Lastly, recommendations related to advanced energy storage materials in solar desalination are noted, assisting researchers to explore efficient water treatment methods.

1. Introduction

Water scarcity is a major challenge in many parts of the world. Although there are abundant water resources on earth, their unequal distribution has lead to limited water resource availability in many parts of the world. In the last few decades, limitations of fresh water supply in developing countries has become a foremost concern, where in response, numerous technologies have been adopted to treat saline water. Desalination processes can separate salt from seawater [1] via various conventional methods including membrane process and thermal process, as summarized in Fig. 1. Often these methods are energy intensive, which makes them very costly in terms of energy consumption.

Although water produced by conventional desalination techniques remains the main source of water for millions of people around the world, these methods are expensive, where power consumption is very high in these processes. Moreover, these systems often cannot be installed in remote areas as each desalination technology has specific operating conditions. Hence, due to the high cost of conventional desalination methods, several other methods have been considered in order to obtain freshwater. Accoridngly, solar desalination has recently emerged as a promising candidate for freshwater production utilizing solar energy. Solar stills are cost-effective and environment-friendly desalination systems in which evaporation and condensation processes occur for freshwater generation. Various authors have investigated different types of solar stills for generating distilled water. Sathyamurthy et al. [3] have assessed experiments using tabular solar still, both with fins as well as without fins, concluding that the freshwater generation of this setup using fins was higher than without fins. This was due to the larger surface area in the setup with fins. Similarly, Dhivagar et al. [4] have investigated the performance of solar stills using conch shells as an energy storage biomaterial, in addition to porous media, in the climatic conditions of Ongole, India. Their results showed that the modified solar still outperformed conventional solar stills in terms of both

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https://doi.org/10.1016/j.rser.2023.113663
Received 26 February 2023; Received in revised form 14 August 2023; Accepted 16 August 2023
Available online 24 August 2023

Nomenclature

Abbreviations

ASV	Annual savage value ($/year)
CRF	Capital recovery factor
CPC	Compound parabolic collector
CPL	Cost per liter ($)
FAC	Fixed annual cost ($/year)
GO	Graphene oxide
HP	Heat pipe
HT	Heat transfer
PCM	Phase change material
PV	Photovoltaic module
M	Average annual productivity (L/m^{2}year)
MWCNTs	Multi-walled carbon nanotubes
MSF	Multi-stage flashing
MED	Multi-effect distillation
NPs	Nanoparticles
SFF	Sinking fund factor
STCM	Solar thermal conversion materials
TEC	Thermo-electric cooler

Symbols

A	Surface area (m^2)
E_{in}	Embodied energy (kWh)
$(E_{en})_{out}$	Energy production (W)
$(E_{xn})_{out}$	Exergy production (W)
G_{co_2}	Environmental parameter (ton $\mathbf{co_2}$)
G_{ex,co_2}	Exergoennvironmental parameter (ton $\mathbf{co_2}$)
h	Convective heat transfer (W/m^2.K)
I	Solar radiation (W/m^2)
h_{fg}	Latent heat of water, (J.kg^{-1}.K^{-1})
K	Thermal conductivity (W/mK)
p_w	Partial Pressure of the vapor at water temperature (Pa)
p_g	Partial Pressure of the vapor at glass temperature (Pa)
q	Heat transfer rate (W/m.K)
T	Temperature ($^\circ C$)
T_i	Mean operating temperature ($^\circ C$)

Greek Letters

ε	Emissivity

Subscripts

Ev	Evaporative
Ex	Exergy
En	Energy
C	Convective
B	Basin
F	Water film cooling
A	Air
G	Glass
W	Water

energy and exergy efficiency by 10.3% and 9%, respectively. In their study, the cost per liter and CO2 emissions were lessened by 11.1% and 10.9% respectively, as compared to conventional cases. Vaithilingam et al. [5] have conducted detailed exergy and energy analysis of acrylic solar stills, both with and without copper fins. Their daily yield of acrylic solar stills both with and without fins was 5.08 kg and 3.75 kg, respectively. Further, the energy and exergy effectiveness of solar stills equipped with copper fins were found to be 32% and 2.81% respectively, and without copper fins at 24.93%, 1.69%, respectively. Negi et al. [6] have experimentally analyzed horizontal and inclined wick types of single basin solar stills with a flat plate solar collector. In their study, the overall efficiency and day efficiency of inclined wick type solar stills with a flat plate solar collector was 22.1% and 16.3% respectively, higher than a horizontal wick solar still system. Further the inclined wick type's maximum daily yield was 3.997 kg/ m^2-day, higher than both the horizontal wick type and conventional solar still systems.

Modi and Gamit [7] have evaluated the impact of aluminum oxide Al2O3 based nanofluid and energy storage material sodium nitrate (NaNO3) on water generation of pyramid solar desalination. Their results indicate that generated water and thermal efficiency of modified solar desalination were 2.15% and 3.2% higher than the conventional case, respectively. In addition to this, in their study theoretical models

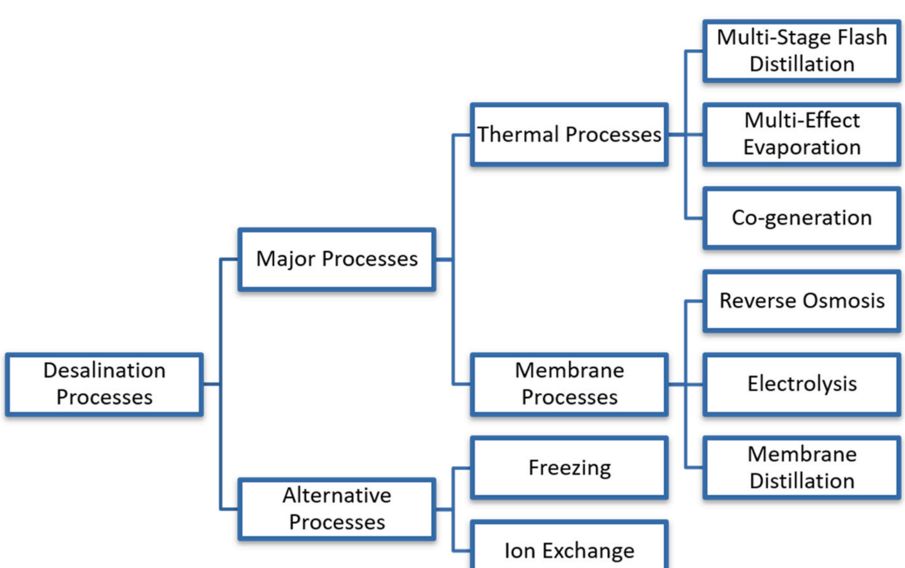


Fig. 1. Major types of desalination process [2].

were developed and compared with experimental results. Further, Mevda et al. [8] have evaluated the influence of energy storage material on the performance of solar still systems. Their outcomes exhibited that the distilled water generation of a conventional system and a system using energy storage material was 1.4 kg/m2 and 2.5 kg/m2, respectively. Additionally, the exergy efficiency and daily efficiency of the modified solar still were increased by 12.55% and 72.6%, respectively.

Saxena et al. [9] have reviewed studies on solar stills and addressed research gaps for future studies focused on both the design of solar stills and their heat transfer mechanisms. Moreover, solar still performance evaluation parameters, such as: design, cost, energy and exergy efficiency, productivity, portability, reliability and sustainability were explored. Techniques to improve the performance of solar stills were also examined, along with economic analysis and feasibility. El-Agouz et al. [10] have presented a detailed theoretical model of a direct contact membrane distillation system powered by solar heat pipe collectors using MATLAB software. They conducted a thorough parametric analysis to determine the effect of design parameters on system performance, with results showing that the number of solar collectors, feed seawater flow rate and cooling water flow rate were the most sensitive parameters impacting the performance of the system. More specifically, they noted that increasing the number of heat pipe solar collectors and the feed seawater flow rate, while decreasing cooling water flow rate, improved the freshwater yield of the distillation system.

El-Agouz et al. [11] further reviewed solar-powered membrane distillation technology, and the various solar thermal feed preheating systems that can be used with it. They critically analyzed solar thermal feed preheating systems including: solar flat plate collectors, evacuated tube collectors, hybrid photovoltaic/thermal collectors, high-concentrating solar collectors, salt-gradient solar ponds and solar distillers. Within their study, these authors noted that additional research is required to enhance the performance of solar-powered membrane distillation by boosting the solar thermal source and improving heat recovery systems. Aboelmaaref et al. [12] have conducted a numerical analysis of an adsorption-based distillation system powered by a solar dish/Stirling engine, with a system designed to produce both electricity and fresh water. These authors evaluated the system performance by analyzing various parameters, such as net electric power, electrical efficiency, specific distilled freshwater productivity, specific cooling power and gained output ratio. According to their findings, the proposed system offered an electrical power output of approximately 23.42 kW, with a solar to electricity efficiency of 23.40%. The system also yielded specific daily freshwater production of approximately 11.53 m^3 per ton of silica gel, 320 W/kg of silica gel specific cooling power and a gained output ratio of 0.62.

Many studies [13–19]have been conducted in the literature to produce distilled water from solar stills. However, the amount of freshwater generated by solar stills remins very low, where this can be improved by using different techniques including: heat pipe/pulsating heat pipes, external condensers, solar collectors, photovoltaic modules, glass cover cooling, phase change materials (PCM), nano powders, nano/PCMs, porous media, as well as some energy storage material/biomaterials. Different energy storage materials have been applied in recent studies to raise the productivity of freshwater by solar stills. Advanced energy storage materials, such as nanoparticles, nano-enhanced phase change materials and phase change materials, can enhance the freshwater productivity of solar desalination. To date, most related research has been performed to enhance water productivity using energy storage materials. Fig. 2 depicts publications related to advanced energy storage materials in desalination, showing an increase in the number of publications during the last five years as data has been taken from "Web of Science". Accordingly, the current review focuses on varied materials and methods that can be deemed effective for enhancing water generation by utilizing solar stills. The review covers various related latent heat storage materials, nano enhanced storage materials, PCM with porous materials as well as heat pipes, all of which are summarized and compared for the first time in this manuscript. This review provides a unique study for researchers, exploring new materials to enhance water production by forming sustainable desalination. The review includes considerations of costs as well as exergoeconomic and CO_2 mitigation analysis of various types of solar desalination using energy storage materials.

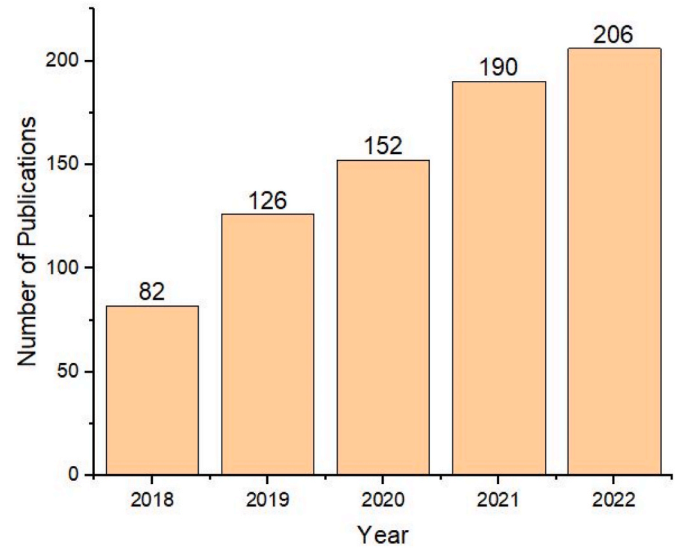


Fig. 2. Number of publications during (2018–2022) having keywords "advance energy storage materials" in "desalination" in Web of Science.

2. Principle of solar still desalination

2.1. Process description

The solar still desalination principle relies on evaporation and condensation, through which impure water is purified [20]. The process of water treatment in a solar still is very simple, as incident solar irradiation heats the absorber surface and enhances the temperature of the basin area of the solar still. Heat is conducted between the basin and the saline water, which leads to the rise of water temperature that assists water vapor. The vapor of water is then condensed on the cover of the solar still and the distilled water is produced. Solar still desalination applications are classified as either active or passive, according to how they work. Within the passive technique, such as using fins, cover glass cooling, shading and others [21], no external equipment or source of energy is used during water production, while in the active technique, external systems are implemented to enhance water production, which may include solar collectors, solar panels (PV/T), thermoelectric heaters, electrical heates and/or panels [22,23]. Various solar still desalination systems, as based on varied categories, are summarized in Fig. 3.

2.2. Advanced energy storage material used in solar desalination

Several studies to date have utilized energy storage materials to improve solar energy applications. Advanced energy storage materials including nanotechnology and PCMs have been shown to improve the generated freshwater of solar desalination systems. Accordingly: adding nano powders in phase change materials as a nano-enhanced PCM; mixing the nanoparticles in black dye or nano-coating the condensation area; and dispersing the nanoparticles in fluid as a nanofluid can all have a high effect on the productivity of solar desalination systems. The mixing of nanopowders in PCM leads to decreasing time of heat transfer rate, and increases the thermal conductivity of a nano-enhanced PCM compared to a regular PCM. The phase change material receives the

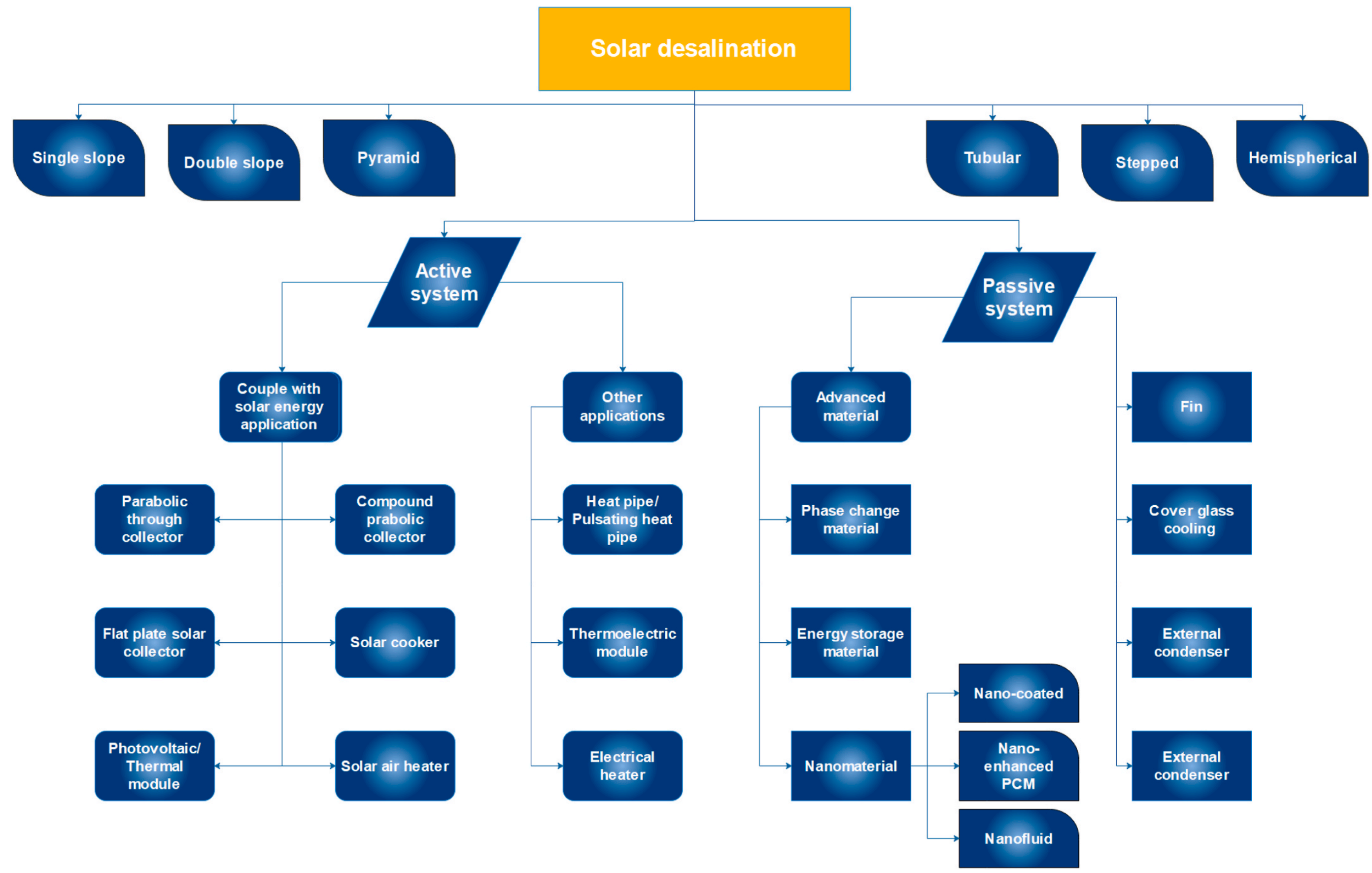


Fig. 3. Various types of solar still desalination [24].

thermal energy of the solar radiation and releases it to the solar desalination when needed. In this present study, a focus on energy materials including nanomaterials, nanofluids, nanoparticles-based phase change materials (PCMs), composite PCMs, PCMs with porous materials, and PCMs with heat pipes have been investigated with regard to their ability to improve solar desalination systems. Fig. 4 indicates the charging and discharging process of the energy storage materials in a typical solar still desalination system.

2.3. Mathematical background of solar desalination

The design of a system can assist in predicting the water output and thermal performance of a system. To design a solar still, thermal heat balance for each element including absorber area, glass cover and saline water should be obtained. Therefore, the mathematical background of each element of the system is discussed below.

2.3.1. Absorber area

The thermal energy of the sun passes through glass and hits the surface of an absorber area, which causes an increase in its temperature. For obtaining balanced energy of the absorber area, the inlet energy of the absorber area is thermal solar energy (solar intensity), whereby outlet energy is the heat loss to ambient and HT by natural convention into the water. The governing Eq. for this relation is as follows [25]:

$$\mathbf{q_{t,b-a} + q_{c,b-w} = \tau_b I_s(t) A_b} \tag{1}$$

where

$$\mathbf{q_{c,b-w} = h_{c,b-w}(T_b - T_w)} \tag{2}$$

$$\mathbf{q_{t,b-a} = h_b(T_b - T_a)} \tag{3}$$

The coefficient of convective HT from absorber area to water is achieved by Ref. [26]:

$$\mathbf{h_{c,b-w} = \frac{k}{L} 0.54 (Gr.Pr)^{0.25}} \tag{4}$$

where L and k present the water height and thermal conductivity. Moreover, Pr and Gr show the dimensionless parameters of Prandtl and Grashof numbers. The HT coefficient from absorber to ambient is achieved by Ref. [26]:

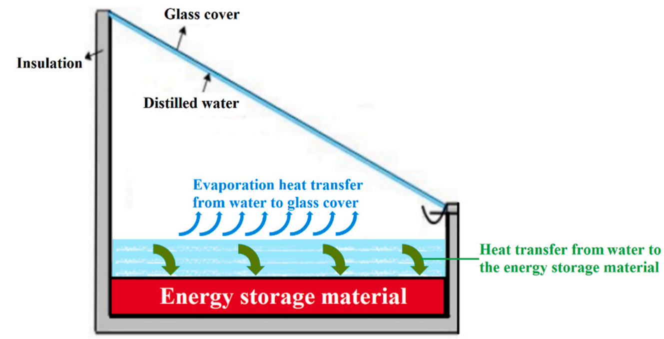
$$\mathbf{h_b = \frac{1}{\frac{1}{\frac{k}{L}} + \frac{1}{h_{c,b-w}}}} \tag{5}$$

2.3.2. Saline water

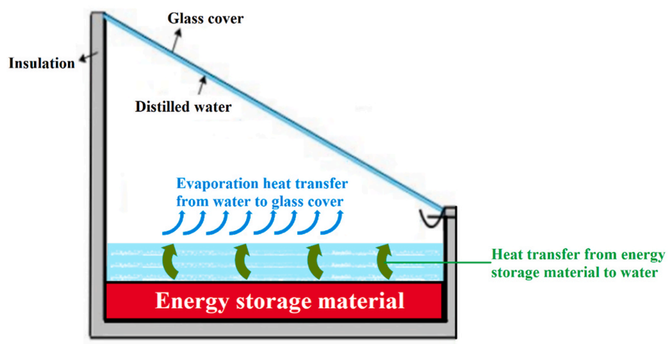
In the passive system, solar irradiation is the main source for producing heat, utilized in order to increase saline water temperature. The inlet thermal heat of saline water in the system is equal to the outlet thermal heat of the absorber area to the water, as well as solar intensity, whereby the thermal heat outlet of the water is equal to total HT from water to the glass. In active solar desalination, the term of another energy source into the water should be considered in deriving the thermal balance of water. Energy relation in saline water is obtained by Ref. [25]:

$$\mathbf{I_s(t)\tau_w A_b + q_{c,b-w} + Q = q_{t,w-g} + (MC)_w \frac{dT_w}{dt}} \tag{6}$$

where Q presents the thermal heat from other sources such as heat pipe/pulsating heat pipe, thermoelectric module and advanced material (PCM and nano/PCM during the night).



a) Charging process during the day



b) Discharging process during the night

Fig. 4. Charging and discharging process of the energy storage material in a typical solar desalination during a) day and b) night.

2.3.3. Glass plate

The cover area is the condensation part of the solar still. By enhancing the temperature of cover and evaporation surface, the water generation of the device increases. The inlet thermal heat input of the glass is solar energy (can be negligible in low thickness), total HT from water to cover, and the outlet thermal heat of glass is specified to glass cooling. The thermal energy relation to the cover is calculated by Ref. [25]:

$$Q_{outet,cooling} = I\alpha_g A_g + q_{C.w-g} + q_{r.w-g} + q_{ev.w-g} \tag{7}$$

The evaporation HT from water to glass is given as [27]:

$$q_{ev.w-g} = h_{ev.w-g} A_g (T_w - T_g) \tag{8}$$

where coefficient of evaporative HT from the Dunkle equation is obtained by Ref. [28]:

$$h_{ev} = 0.016273 \times h_{c,w-g} \times \frac{P_w - p_g}{T_w - T_g} \tag{9}$$

where the $h_{c,w-g}$ presents coefficient of convection HT from glass to water, and is calculated by Ref. [29]:

$$h_{c,w-g} = 0.884 \times (\Delta T')^{\frac{1}{3}} \tag{10}$$

$$\Delta T' = \left[(T_w - T_g) + \frac{(P_w - p_g)(T_w)}{268.9 \times 10^3 - P_w} \right] \tag{11}$$

$$P_w = \exp\left(25.317 - \frac{5144}{T_w}\right) \tag{12}$$

$$P_g = \exp\left(25.317 - \frac{5144}{T_g}\right) \tag{13}$$

where p_g and p_w depict the partial pressure of vapor on glass and water, respectively. The cumulative HT from water to glass is given by Ref. [25]:

$$h_{total.w-g} = h_{ev.w-g} + h_{c.w-g} + h_{r.w-g} \tag{14}$$

$$h_{r.w-g} = \varepsilon_{eff}\sigma\left(T_w^2 + T_g^2\right)(T_w + T_g) \tag{15}$$

where ε_{eff} illustrates the effective propagation and is obtained by Ref. [26]:

$$\varepsilon_{eff} = \left(\frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_g} - 1\right) \tag{16}$$

The produced water by solar still is given by Ref. [30]:

$$\dot{m}_{hourly} = 3600 \times \frac{q_{ev.w-g}}{h_{fg}} \times A_w \tag{17}$$

where h_{fg} shows the latent heat and is achieved by Ref. [30]:

$$h_{fg} = 2.4935 \times 10^6 \left(1 - 9.4779 \times 10^{-4}(T_i - 273) + 1.3132 \times 10^{-7}(T_i - 273)^2 - 4.7947 \times 10^{-9}(T_i - 273)^3\right) \tag{18}$$

where T_I is calculated as following relation:

$$T_i = \frac{T_w + T_g}{2} \tag{19}$$

3. Advanced energy storage materials for potable water

The major climate factors affecting solar still performance are solar irradiance, ambient temperature and wind velocity [31]. Different parameters that impact the efficiency of solar stills include: mass flow rate of feed water; solar still surface area; basin water depth; usage of PCM materials; use of materials that help water evaporation i.e., porous surfaces; nanoparticles; use of fins; and external solar collectors [32,33]. Advanced energy storage materials are gaining popularity as passive cooling techniques for thermal management purposes [34]. The utilization of these materials, including phase change materials (PCMs) and nanomaterials for water generation in solar stills, has a significant impact on water production. As the thermal value of nanomaterials is high, more energy can be saved, which results in reducing the time required for producing water. Nanomaterials can be synthesized in required shapes and sizes depending on the application, such as nanoplatelets, nanotubes, nanoparticles, nanowires and others. The dispersion of solid particles in water has significant potential in HT. Nanomaterials are used to raise HT rate by increasing "h" due to an increase in "k" [35]. Hence, the overall productivity of potable water is increased by using these materials under the effects of solar radiation.

3.1. Nanomaterials for solar desalination

Solar energy for clean freshwater production has been utilized in recent times as a result of: its low-cost, the availability of renewable energy sources, its unlimited sources of energy, zero pollution, and it being environmentally friendly. To date, there has been an absence of research regarding the cleaning of water utilizing nano powders in base fluid. Accordingly, the notion of utilizing nanoparticles (NPs) for the efficient thermal performance of fresh water is presented in this paper, whereby the amount of "k" of these nanomaterials is significantly higher. In this way, particles suspended in base water have better thermal performance. Three methods have been discussed here that improve water productivity by solar desalination including nano-coated, nanofluid and nano/PCM methods.

3.1.1. Nano-coated materials in solar desalination

The nano-coated technique can be considered for increasing evaporation and condensation rates of solar desalination. Adding nanoparticles with black dye to cover the absorber area increases the absorption of solar irradiation, which in turn increases natural convection. Thakur et al. [36] have assessed the efficiency of solar stills using Al_2O_3 nano powders mixed with black dye coated on the absorber surface area, where it is also mixed with water. Both these techniques can cause an increase in the production of water. Results indicate that in both experimented cases, water productivity increased by 24.3% in comparison with the conventional system. Sharshir et al. [37] have reviewed the performance of solar stills using nano-coated, wick media and water-cooling layers on the efficiency of tubular solar stills. Accordingly, cobalt oxide nano powders were mixed in order to cover the wick material, as means to increase HT rate between the absorber surface and the water. The outcomes of their study showed that these modifications can improve the productivity of water, whereby the productivity of water enhanced by 82.5%. Thermal and exergy performance improved by 68.14% and 119.1% respectively, while maximum cost saving in the freshwater price was 39.14%. Kabeel et al. [38] have explored the influence of water height and titanium oxide/black paint nano-coatings on solar still water productivity. The height of the water varied from 0.01 m to 0.035 m. Further, the results indicated that the water productivity of this device using nano-coated materials increased by about 6.1% compared to a system without nano-coated materials.

Zanganeh et al. [39] have assessed the effect of silicone nano-coating on condensation surfaces of solar still productivity, whereby the authors considered nano-coated materials to change condensation from film to dropwise mechanism. According to their results, the productivity of solar stills with film condensation was 4828 ml/ m^2, while the productivity in the case of dropwise condensation was 5807 ml/ m^2. Thakur et al. [40] have changed the glass cover wettability by spraying nano-coated materials to increase the distilled water generation of solar stills. A silicon nano-coating was utilized on the glass cover, whereby results depicted that the water output of the device increased by 15.6% as compared to traditional glass cover. Gangavathi et al. [41] have designed, constructed and experimented a solar still using nano-coated material to raise the condensation rate. Fumed silica nanopowder was used to prepare the nano-coated material. The authors illustrated that the new configuration enhanced water productivity by 28.53% in comparison to the conventional form. Thakur et al. [42] have concluded that the efficiency of solar stills could be increased by a combination of nano-coated materials sprayed on the condensation area of cover with silicon nanoparticles and nano-coated dispersed in black paint in the evaporation area of absorber plate with graphene oxide NPs. It was then concluded that the proposed configuration produced freshwater of 3410 ml/day. Results revealed that the viability of nano-coated materials used on the glass cover and absorber plates improved condensation and evaporation, respectively. In addition to this new configuration producing 3410 ml/day of freshwater, as noted above, the configuration also enhanced the energy and exergy efficiency of solar stills by 37% and 112%, respectively.

In recent decades, direct solar steam generation has been investigated as a means to produce fresh water at a high evaporation rate, resulting in higher efficiency compared to conventional techniques [43,44]. Studies have shown that these types of systems are 90 % effective for this purpose [45–48]. Solar steam generation is a portable, efficient and environmentally friendly device [49,50], where NPs can be dispersed in water to absorb solar energy and produce vapors. Further, small-scale NPs have a high value of “k”, which results in an enhanced rate of evaporation. These NPs, when dispersed, create nucleation sites that enhance vaporization, as depicted in Fig. 5. The radiations incident on the surface is then converted into thermal energy, which in turn

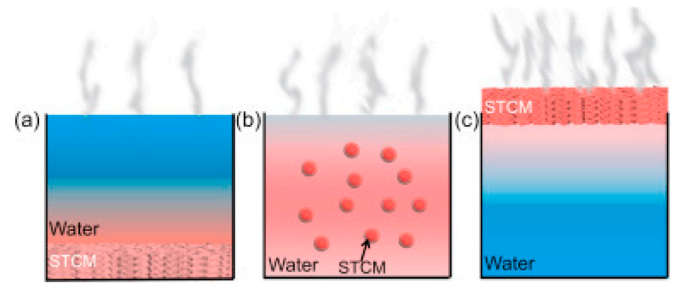


Fig. 5. Various positions of solar thermal conversion materials (STCM) in water [51].

enhances the evaporation of water.

The rate of evaporation is a vital factor during experimentation, used to estimate how much water can be produced from a solar simulator. The evaporation rate largely depends upon the amount of solar radiation incidents and how much energy is stored in energy-storing materials. In this way, more water can be produced if more nucleation sites are created. All these factors should be considered during the preparation of setup for potable water production.

3.1.2. Nanofluid in solar desalination

In this paper, a mixture of nanoparticles and base fluids have been considered to raise freshwater production in solar stills. Nanofluids alter the thermal characteristics of the fluid and enhance HT and absorption capacity of solar still systems. Nazari et al. [52] have assessed the influence of CuO-water nanofluids instead of water, and cover cooling on the water generation of a solar still. The ambient air temperature decreases by thermoelectric cooler (TEC) and flows on the cover via a fan. The results of the paper noted above displayed that water productivity, energy and exergy efficiencies were enhanced by 81%, 80.6%, and 112.5%, respectively. In addition, the optimum productivity of the modified system was $0.0218/L. Sharshir et al. [53] have presented a comparison study of solar desalination by graphite and copper oxide nanofluids with traditional solar desalination. Further, the tests were conducted for water cover cooling rates from 1 to 12 kg/h. The results showed that the freshwater output of the modified solar desalination was enhanced by 47.8% and 57.6% respectively, as compared with traditional modes. Shoeibi et al. [54] have experimentally and theoretically evaluated the influence of different nanofluids and TEC on the efficiency of solar stills. Aluminium oxide/water, titanium oxide/water, MWCNT (Multiwalled carbon nanotube)/water and copper oxide/water nanofluids were considered to raise solar still productivity. The results implied that the highest increase in productivity of the system was 11.57% which occurred in the MWCNT-water nanofluid. Elmaadawy et al. [55] have assessed the impact of carbon black/water nanofluid, wick and gravel, as well as cover cooling on the freshwater output of solar desalination. Various modifications of the system were considered, such as a system by gravel and nanofluid, a system by gravel and wick material and a system with gravel, wick and nanofluids. Their outcomes displayed that the highest freshwater output, energy and exergy efficiencies were raised by 68%, 50.6% and 146.3%, respectively. Nazari et al. [56] have investigated the freshwater output of a solar still by TEC and copper oxide/water nanofluid. In their study, the vapor of water goes to the channel, in which the thermoelectric cooler was installed and then flows to the water heater tank. The results indicate that freshwater output, exergy and energy efficiencies of the modified system was raised by 38.5%, 38.9% and 31.2%, respectively. Further, by mixing a concentration of 0.08% of CuO/water nanofluid, the water output was enhanced by 82.4%. Parsa et al. [57] have assessed the efficiency of various configurations of solar desalination, such as: a system using TEC; a system using TEC and Ag/water nanofluid; and a system using Ag/water nanofluid and TEC with an external condenser. The temperature of one side of the external condenser decreased by water flow rate, whereby another was reduced with a thermoelectric cooler. The researchers indicated that the freshwater output and thermal efficiency of the system using nanofluids and external condensers enhanced by 100.5% and 26.7%, respectively. The impact of a thermoelectric cooler, nanofluids, and vibration movement on the water output of solar desalination was assessed by Dawood et al. [58]. In their study, the copper oxide nano powders were dispersed in saline water with a volume fraction of 0.5%, 1%, and 1.5%, respectively. The direct current motor was installed under the springs, and was considered to shake the solar desalination enclosure. The TEC was installed on the cover to reduce the cover temperature. On the one hand, the results indicated that the productivity of the system using shaking and cover cooling, and the system using shaking without cover cooling at a volume fraction of 1.5%, raised results by 212.2% and 47.9%, respectively.

On the other hand, other studies have investigated the reduction of glass cover cooling via nanofluids. Shoeibi et al. [59] have performed a comparative study of double slope, hemispherical and tubular solar stills using aluminum oxide/water nanofluid cover cooling to improve the condensation rate. Aluminum oxide nano powder at a volume fraction of 0.1% was mixed with water flowing over the glass cover at a velocity of 0.1 m/s. The results depicted that the water output of the double-slope system was improved by 2.8% and 4.8% respectively, as compared to hemispherical and tubular systems. Shoeibi et al. [13] have numerically explored the use of hybrid nanofluid to reduce the cover temperature of double slope solar stills, thereby increasing the temperature difference between the evaporation and condensation areas. The combination of aluminum oxide/titanium oxide/water with a volume fraction of 0.4% was considered as hybrid nanofluid, where the optimal concentration of nanoparticles was gauged as 0.45%, whereby the water output and energy efficiency of the solar still was enhanced by 11.09% and 28.21%, respectively.

3.1.3. Nano-PCM in solar desalination

Phase change materials (PCMs) act as heat storage materials in solar energy applications, where by raising their thermal properties, the performance of solar energy applications during low solar radiation increases. A nano-PCM stores the thermal energy taken by solar energy during the day, where it is removed at low solar radiation, which in turn increases the distilled water of the solar desalination. Nano powder mixing in base PCM improves the speed of taking and removing heat energy. Chamkha et al. [60] have assessed the influence of MWCNT/paraffin composite as a nano-phase change material on the freshwater output of solar desalination. The thermal properties of the composite material in the study were improved by adding the MWCNTs in the paraffin. The results indicate that the water yield of the device using MWCNT/paraffin and paraffin improved by 24% and 19.6%, respectively. Rajasekhar and Eswaramoorthy [61] have increased the efficiency of solar stills by mixing aluminum oxide into paraffin wax. The effective absorber sheet area of the solar desalination was measured at 1 m^2. The researchers displayed that the thermal efficiency of the device by PCM and nano/PCM was 40% and 45%, respectively. Kabeel et al. [62] have conducted the influence of tubular solar desalination system by a combination of PCM and nanoparticles. Accordingly, the graphene oxide NPs were mixed in paraffin wax to improve its performance. Their results illustrated that no significant increase in the thermal properties of graphene oxide/paraffin at a concentration under 0.3% was achieved. Further, the freshwater generation of the systems using PCM and nano/PCM increased by 29.3% and 216.9%, respectively. The daily efficiencies of solar still types of conventional, PCM and nano PCM were 23.48, 30.31 and 50.85%, respectively.

Goshayeshi et al. [63] have assessed the influence of nano/PCM on the distillation output of solar stills. The mixing of graphene oxide NPs at various concentrations with paraffin was considered to keep the water temperature high inside the system. The authors showed that the generated water of the device by this configuration was improved. Kumar et al. [64] increased solar desalination productivity by adding silica nano powders into the paraffin wax. The silica nano powders were mixed in 10 kg of paraffin wax with a volume fraction of 0.5% to raise the energy efficiency of the device. The researchers showed that the water generation of the systems with nano/PCM and PCM raised by 67.07% and 51.22%, respectively. Rufuss et al. [65] have studied the freshwater generation of a solar still by nano/PCM, where CuO nanoparticles at a volume fraction of 0.3% were mixed in paraffin to develop a nano/PCM composite as an energy storage material. The absorber sheet area of the basin was 0.5 m^2, whereby a storage enclosure with a depth of 0.02 was manufactured to fill the nano/PCM. The results showed that the freshwater output of the solar still by nano/PCM was increased by 35% compared to the system using PCM. The influence of the composition of paraffin and different volume fraction of copper oxide nanoparticles on the productivity of solar still was evaluated by Behura et al. [66]. The time speed of receiving and releasing the heat energy of CuO/paraffin was decreased in comparison to PCM. The outcomes indicate that freshwater generation of the system by nano/PCM at weight concentrations of 0.1, 0.2, and 0.3% were 1.76, 1.82, and 2.04 L/m^2.day, respectively.

Abdullah et al. [67] have investigated tray solar stills modified with a wick fin absorber, nano/PCM and reflector mirrors. In their study, three electric heaters were used to heat the water basin and to power a photovoltaic cell, which was placed behind the solar still. According to the results, the modified tray solar enhanced the water productivity by 166% and 136% respectively, when using heaters and nano/PCM, as compared to the conventional case. The daily yield was enhanced by 196% when both the heater and nano PCM were used, as compared to the simple case.

Sonker et al. [68] have analyzed solar stilsl with PCM, nano/PCM thermal energy storage mediums filled in copper cylinders. Their results indicated that the yield of solar still increased by 43.5% when nano-PCM was used in comparison with the conventional case, where its yield increased by 32.90% when PCM was used compared with simple case. A cost reduction of 40% was observed, where the payback period was determined to be 4.3 years. Selimefendigil et al. [69] have evaluated the performance of single slope solar still by enhancing it with PCM, CuO nano PCM and a CuO nano-enhanced absorber coating. Their results indicated that the use of nano PCM and nano-enhanced coating enhanced the yield by 26.77% as compared to the conventional case. Abdelaziz et al. [70] have improved the performance of tubular solar still using nano-enhanced PCM, where their experimental setup is depicted in Fig. 6. The cases that were under consideration in their study were a V-corrugated aluminum basin, a wick with a V-corrugated aluminum basin, adding carbon black to the wick material in a v-corrugated aluminum basin, and PCM with a v-corrugated aluminum basin. It was concluded in their study that the productivity of water increased to 88.84 %, with the highest occurring in the case of the PCM combination.

Kandeal et al. [71] have utilized copper chips along CuO nanoparticles in water, together with PCM, for performance improvement of double-slope solar stills. CuO nanoparticles were added to water in 1.5 wt% and added to PCM in 15 wt%. Their results showed that the use of a water nanofluid, nano PCM and copper chips submerged in a water nanofluid resulted in yield, energy efficiency and exergy efficiency enhancement of 113%, 112.5%, and 190% respectively, in comparison to traditional forms. Abdullah et al. [72] have experimentally studied novel convex-shaped solar stills and utilized nano black paint, nano-enhanced PCM, various wick materials, and various convex heights. By using a convex solar still, nano black paint and nano-enhanced PCM, water productivity was enhanced by 54%, 18%, and 40%, respectively, in comparison to traditional cases.

3.2. PCM based solar still desalination systems

Utilizing PCM in solar desalination has been applied by many researchers in recent years, whereby a range researchers [73–77] have

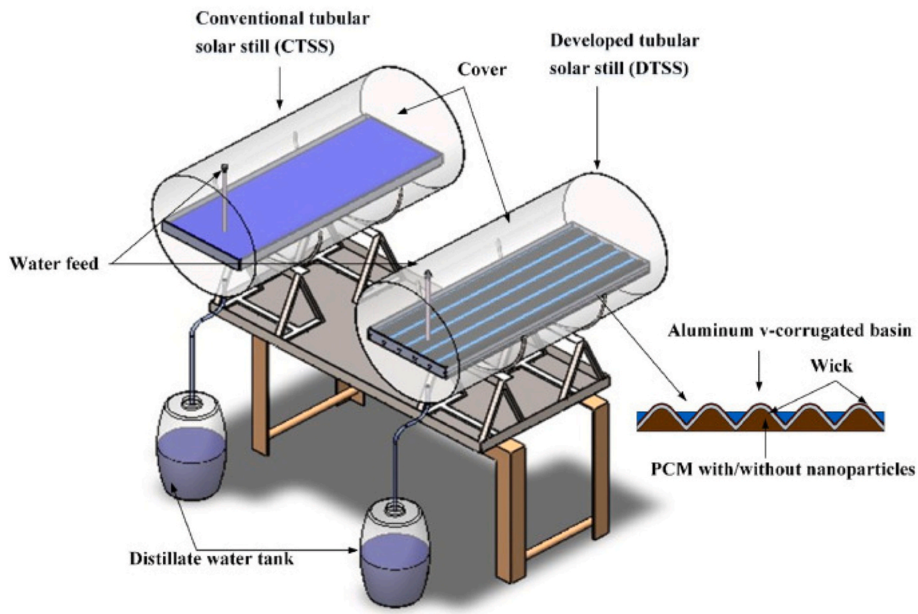


Fig. 6. Experimental setup proposed by Abdelaziz et al. [70].

used various types of PCMs to enhance the freshwater generation of solar desalination. Compared with traditional water storage, PCM media have some major advantages. The major benefits of PCM materials include their high heat energy storage capacity, and receiving and removing thermal process at a close temperature. PCMs can be categorized into inorganic, organic and eutectic, with varied thermal characteristics [78].

3.2.1. PCM based passive solar stills

Passive solar stills do not require solar collectors or external sources for pre-heating water. This kind of solar still is easy to build and maintain, where direct solar radiation is used for water production. Passive solar desalination can be classified into either single or multi-slope solar stills, with the latter having more than one slope. These systems can be further improved by using PCMs. Accoridngly, the PCMs absorb the heat energy of solar intensity in the daytime and utilize this heat when solar energy is not available, such as during nighttime or cloudy weather conditions. The first passive solar still utilizing PCM was investigated by Naim and Kawi [79], in which paraffin wax, water and paraffin oil were used. Their multi-basin solar still produced a maximum water output of 4530 mL/ m^2 for a duration of 6 h.

Many researchers have illustrated that integrating PCM into solar stills enhances the productivity of water [80–84]. The major advantage of using PCM is that its energy is stored during the day, where it can later be used in the production of water during the night. Utilizing PCMs in solar desalination studies have been completed by Mousa et al. [85]., exploring the utilization of candle wax (tricosane) PCMs in solar desalination systems. In their study, the fraction of PCM to water was varied as 0, 0.17, 0.35 and 0.51, where PCM was filled in copper tubes submerged in water. The authors concluded that PCM had a negative impact on water yield during the daytime, while during night-time the water production was directly proportional to the amount of PCM. The efficiency of fin-type solar desalination as an energy storage material has been investigated by Sarhaddi et al. [86], evaluating the effects of different variables including atmospheric temperature, wind speed, and irradiations on the performance of solar desalination. According to their results, on a semi-cloudy day, the maximum exergy and energy efficiencies for a system using PCM were 8.59% and 74.35%, respectively. Attia et al. [87] have evaluated the influence of PCM and a wick convex basin on the performance of hemispherical solar desalination systems. The findings of their experiments showed that generated freshwater, energy and exergy efficiencies of the system using the energy storage material were enhanced by 87%, 85.6% and 128.2%, respectively.

Farhan et al. [88] have also enhanced the performance of solar still for water productivity by using PCM. They used a paired basin as well as four-lateral glass face solar stills to increase the generation of water. Their tests were performed in the climate of Karbala city in Iraq in October and November. Their results concluded that an hourly increase in water production of approximately 25–40 % was observed. Sampathkumar and Natarajan [89] have increased the production of water of a single slope solar still by applying agar-agar fibre in the basin's surface using a micro PCM. Varied weights of 5, 10, 20, 30 and 40 g of agar-agar fibre were used in the absorber basin for these experiments. Their results concluded that PCM with 20g weight of agar-agar fibre has a better value of "k" than single PCM. The maximum thermal efficiency was improved by 44 % by using PCM with agar-agar fibre as compared to a conventional one. In another study, Abdelgaied et al. [90], have experimentally and theoretically explored the thermo-economic performance of hemispherical solar desalination systems using CuO-water nanofluid and PCMs. Their outcomes revealed that the generated water productivity of the solar desalination system using CuO-water nanofluid and PCM was 80.2% higher than the conventional solar desalination, whereby the cost of freshwater yield was lowered by 75%. Hammad et al. [91] have investigated the use of a v-corrugated basin, PCMs, and longitudinal copper fins embedded inside the PCM container to improve the performance of a solar desalination system. According to their findings, the modified solar still produced 63.57% more freshwater than the conventional system, with an energy efficiency of 72.70%, and a cost reduction of 23.10%.

Kabeel et al. [92] have designed and analyzed the performance of solar stills with a v-corrugated basin integrated with a reversed solar collector in the same outdoor conditions of El-Oued, Algeria. Their results indicated that the daily production of the modified solar still was 68.82% higher than the traditional forms. Moreover, the daily energy efficiency of modified and traditional solar still was 59.70% and 35.52%, respectively. The modified solar collector reduced the cost of water production by 27.12% compared to conventional solar still.

Kateshia and Lakhera [93] have further measured the performance of solar stills using various PCMs like fatty acid, lauric acid, palmitic acid and stearic acid with pin-fins, and compared them to conventional solar stills. Four varied cases were studied, including a traditional system, a system using lauric acid with pin-fins, a system using palmitic acid with pin-fins, and a system using stearic acid with pin-fins. The whole process is shown in Fig. 7, where experiments were performed and maximum accumulated water output was observed in the case of the system with stearic acid with pin-fins, measured at 5.74 L/ m^2/day with an energy efficiency of 56.2 %.

An increase in the condensation area of a solar still enhances generated water of solar stills. This can be raised by using double glass solar stills, triangular solar stills, pyramid solar stills or cascade solar stills [94–96]. The enhancement in the condensation area of solar stills reduces the condensate layer thickness; thus, improving the HT rate, which in turn raises water productivity. Benhammou and Sahli [97] have numerically studied a solar desalination system integrated with double-glazing latent heat storage media, whereby their transient model was developed for performance estimation of solar stills in Algerian Saharan climatic conditions. Their results revealed that PCM provided heat to solar desalination throughout the night for a period of 20 h. The increase in yield during day-time, night-time and at a daily level were 44%, 35% and 63% respectively, compared to the traditional system. It was indicated that an increase in the mass of PCM negatively influenced useful energy. Further, the optimum slope angle in the summer season was found to be 15°. Alshammari et al. [98] have applied multi-effect tubular solar desalination to measure water productivity, where a secondary effect was generated to minimize heat loss by using a tube. The researchers also investigated double, triple, and quadrilateral tubular solar stills, concluding that they can enhance water productivity by 60.5 %, 97.8 %, and 122.4 %, respectively. Sathyamurthy et al. [99] have performed experiments on triangular pyramid solar still with paraffin wax as PCM, whereby they carried out different tests and noticed that the absorber temperature was nearly equal to PCM temperature in the morning, which then increased during the afternoon, and remained constant after that. Saline water with a mass of 20 kg was used, where thermal efficiency and freshwater output were enhanced by 35 % and 100 %, respectively. Abdelgaid et al. [100] have completed experiments to increase the efficiency of tubular solar stills using hollow and circular fins along with PCM. They conducted two tests, in which one test was done with only a hollow and circular section with a tubular solar still, and the other was done along with PCM. The schematic drawing of both setups is displayed in Fig. 8, where the results concluded that PCMs using hollow circular fins enhanced the total water output to 7.89 L/ m^2/day, and showed a 90.1 % increment in performance of the modified solar still.

Kannan et al. [101] have studied hemi-spherical solar stills with PCM encapsulated in aluminium cans of both triangular and square patterns. Their results illustrated that solar still generation of water was enhanced by 92.8% and 67.12% respectively, when using square and triangular patterns of PCM cans as compared to the traditional case. Ajdari et al. [102] have explored an inclined stepped solar still with baffles, PCM, and nanofluid for enhancing yield. The nanoparticles that they used were CuO and GO, in concentrations of 0.01, 0.02 and 0.03% weight fraction, whereby the flow rate of the nanofluid varied. The outcomes indicated that 0.03 wt% of CuO and GO of NPs enhanced water production by 48.12% and 81.59%, respectively. Further, the inclusion of PCM increased water generation by 32.8%. Subramanian et al. [103] have further recorded tests on pyramid-shape solar desalination with PCM, whereby their experimental setup is illustrated in Fig. 9. Their design was completed on this setup, with results showing that the generated water of the conventional solar still was 1610 mL/day, whereas it was 2250 mL/day with the modified device. Accordingly, productivity was raised by 50 % using this newly designed solar still.

A summary of works completed by various authors with regard to PCM-based passive solar desalination is summarized in Table 1. Authors have investigated varied solar stills with the aid of PCMs as well as NPs, leading to improved water productivity. The results suggest that the maximum water generation of solar desalination using PCM can be achieved in pyramid solar desalination system paraffin wax, at a level of approximately 8.1 L/m^2/day.

3.2.2. PCM-based active solar stills

Various solar applications, such as flat plate solar collectors, evacuated tube solar collectors, PV/Ts, electrical heaters, solar cookers, and heat pipe/pulsating heat systems have been widely used in recent years in solar desalination applications. However, the performance of these solar systems has been very low, wherbey this can be raised by using different materials, including PCMs, nano-enhanced PCM, nanomaterials and energy storage material/biomaterials. In this way, a flat plate solar collector that possesses operating fluid in its tubes can be

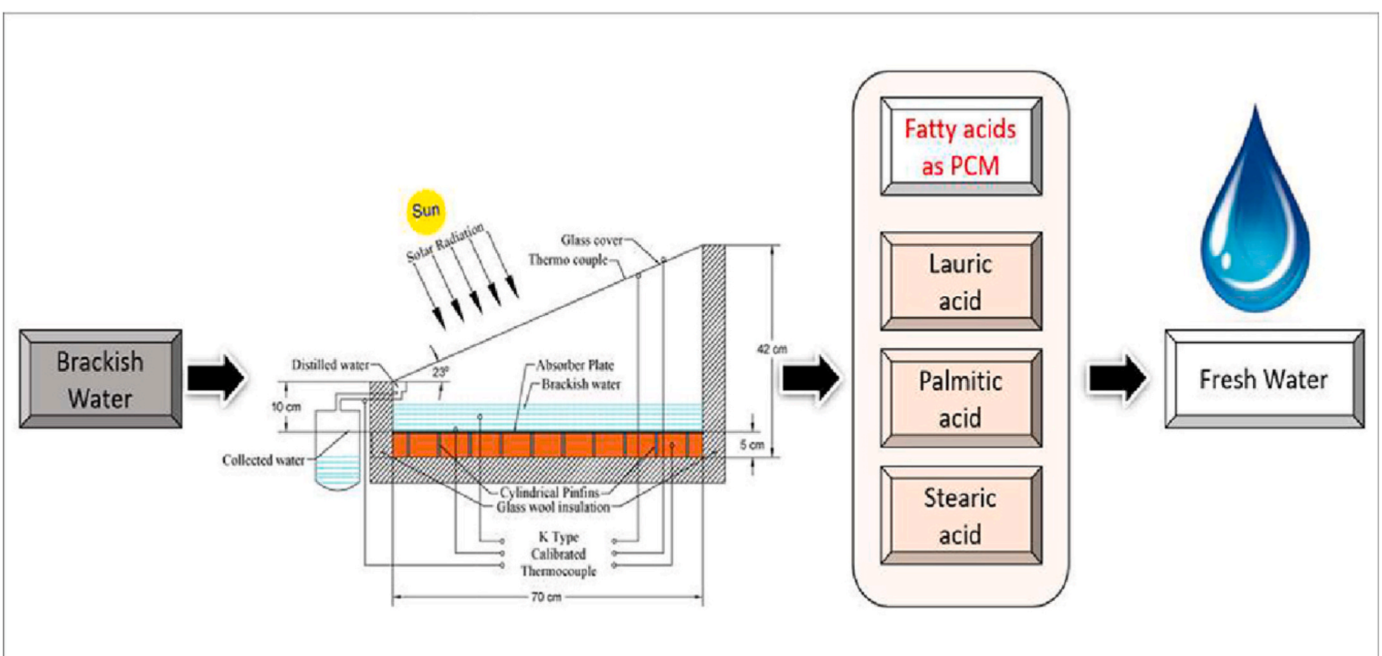


Fig. 7. Whole process for experimentation proposed by Kateshia and Lakhera [93].

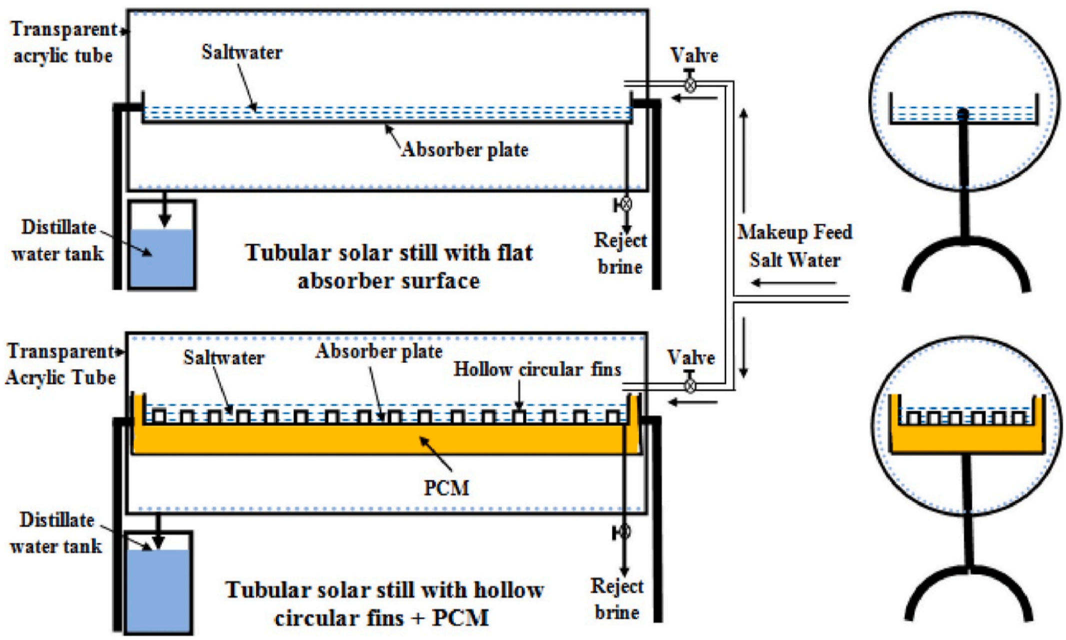


Fig. 8. Schematic diagram of PCM-based scenario of experimental setup [100].

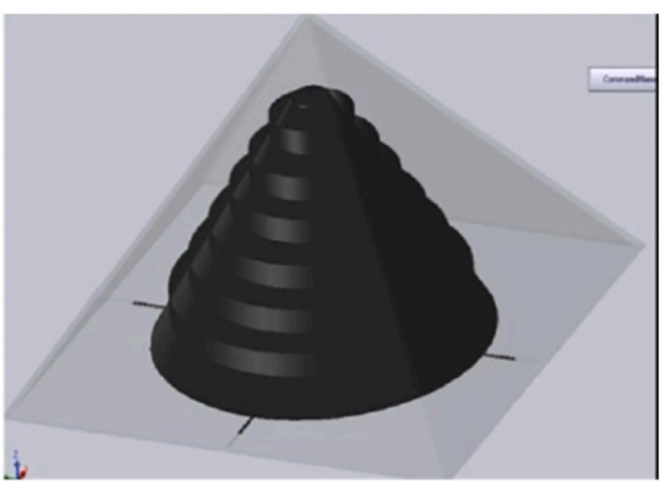


Fig. 9. Real experimental setup of pyramid shape solar still [103].

utilized for absorbing solar energy. A flat plate solar collector using PCM has been considered by various researchers [119].

Abu-Arabi et al. [120] have performed theoretical modelling of solar stills coupled with glass cooling, flat plate solar collector and PCM. The effect of various parameters, such as hot water flow rate, cooling water flow rate, PCM mass, solar irradiation, wind speed and ambient temperature have been explored. The optimal mass ratio of water to PCM was found to be 2:1, whereby a high melting point and high latent heat of fusion was recommended as the best choice. The productivity of water was shown to be significantly enhanced by varying the under-consideration parameter, whereby for enhanced solar stills, productivity was 2.3 times higher than for conventional solar stills.

Harahsheh et al. [121] have studied self-powered solar stills with an external solar collector and PCM. In their study, black-painted stainless-steel tubes filled with PCM were installed under the solar still, whereby performance was explored using parameters of hot water flow rate, solar intensity, surrounding temperature and wind velocity. According to their findings, adding PCM enhanced the water output of the solar still by 50%, whereas usage of an external solar collector improved the water output of the system by 350%. Toosi et al. [122] have explored stepped solar desalination by an external condenser and PCM for improving water productivity, whereby an diagram of their setup is displayed in Fig. 10 (a, b). A fan was attached at the top of the solar still for transferring the water vapor to the condenser, with results showing that the combined use of PCM and external condenser enhanced water productivity by 104%.

Tuly et al. [123] have used a combination of PCM, fins, wick, and auxiliary condensers to analyze the productivity of solar stills, exhibiting a maximum attained water output of 3.07 L/ m^2, as compared to a traditional system of 2.46 L/ m^2. Their improved solar desalination with and without an external condenser provided 39.74% and 30% efficiency respectively, indicating the benefit of using an auxiliary condenser. Essa et al. [124] have utilized PCM, nanoparticle coatings, a parabolic solar concentrator and a rotating cylinder to raise the water output of a tubular solar desalination system. Nanoparticle coatings on the surfaces of the drum and solar still basin were applied to enhance the condensation to dropwise mechanism. According to the study's findings, a highest thermal efficiency of 63.8% was attained by a solar still with a parabolic solar collector, nanoparticle coatings and PCM, with a production enhancement of 218 %. Hafs et al. [125] have numerically studied active and passive single basin solar stills by employing PCM filled-in corrugated surfaces of different shapes and a parabolic trough collector. They displayed that a conventional system with a corrugated area of rectangular protrusions enhanced freshwater yield by 109% and 42% respectively, as compared to conventional and flat surface cases. Further, the solar still with an active case, i.e., with a parabolic trough collector and rectangular absorber, provided a yield of 15.39 kg/ m^2/day as compared to the passive measurement of 2.37 kg/ m^2/day. Sathish et al. [126] have explored hemispherical solar stills by employing PCM, dual reflectors and an insulator cover on the top surface, as depicted in Fig. 11 (a, b). The tilt angle of the reflectors was optimized, wherbey PCM thermal performance was enhanced by embedding aluminum powder. Their results showed that the suggested system enhanced yield and energy efficiency by 115% and 100%, respectively. Moreover, the cost of freshwater per liter and the payback period were reduced by 18% and 19%, respectively.

Elashmawy et al. [127] have conducted a study on a tubular solar still integrated with a parabolic solar concentrator and with novel PCM-filled aluminum tubes, as shown in Fig. 12. Copper rods were

Table 1
Various studies were performed on PCM-based passive solar desalination.

Type of solar still	Location	PCM material	Water productivity	References
Single effect solar still	Iraq	Paraffin wax with alumina NPs	4.0 kg/ m^2/day	[104]
Single effect solar still	India	Paraffin wax	3.2 L/ m^2/day	[105]
Single effect solar still	Egypt	Paraffin wax	Water productivity was in the range of 3.262–4.08 kg/ m^2	[106]
Pyramid type solar still	Egypt	Paraffin wax	8.1 L/ m^2/day	[107]
Pyramid solar still	China	Shaped stabilized PCM	3.41 L/ m^2	[108]
Finned solar still	Bangladesh	Paraffin Wax	2.28 L/ m^2	[109]
Single slope solar still	India	Paraffin Wax	4.08 L/ m^2/day	[110]
Single effect solar still	Pakistan	Paraffin Wax	4.5 L/day	[111]
Single slope double effect	Nigeria	Pure Paraffin Wax	–	[112]
Inclined single basin solar still	India	Paraffin Wax	5.62 L/day	[113]
Single effect solar still	India	black color glass	1.4 kg/ m^2	[114]
Single effect solar still	India	Various Fatty acids	4.43 L/ m^2	[114]
Single effect solar still	India	Paraffin Wax with fins	3.25 L/ m^2/day	[115]
Single-slope solar still	Tehran, Iran	Salt hydrate	456 g/day	[116]
Tubular solar still	Coimbatore, India.	Paraffin wax with candle soot derived carbon NPs	5.71 kg/ m^2/day	[117]
Single slope single basin solar still	Meknès city, Morocco	Paraffin wax	4.08 kg/ m^2/day	[118]

implanted inside the PCM to augment the thermal performance of the PCM. Moreover, the tubes were painted black in order to achieve high absorption efficiency. The authors showed that the yield and efficiency of the solar still improved by 40.51% and 38.25% respectively, as compared to a device without PCM.

Mariduri et al. [128] have performed a study based on the use of PCM in solar stills integrated with a solar collector. Their experiments were performed using different depths of water, set at 0.01, 0.02 and 0.03 m, with double slope basins. A solar collector with paraffin wax was used during the tests, with results depicting that water generation was more at lower depths, whereby solar still productivity was increased to 22 %. Al-harahsheh et al. [129] have conducted experiments to measure the impact of a solar collector with phase change materials, whereby different flow rates were used to check the effect of condensing glass. The results concluded that when using this configuration, water production was at 4.3 L/ m^2/day. A summary of different studies conducted by various researchers related to PCM-based active solar desalination is displayed in Table 2. Different authors have investigated varying solar stills with the aid of PCM as well as NPs and improved water productivity. As observed, the use of paraffin wax with a combination of nanoparticles faciltates an important improvement on generated freshwater of solar stills. This is due to the reduction in time speed of storage and in removing the thermal energy of solar radiation.

3.3. PCM-porous materials for solar still desalination

The productivity of solar still desalination can be increased by using porous materials along with energy storage materials. This type of combination has also been shown to be efficient, and to improve solar still water productivity. Shoeibi et al. [142] have investigated solar stills utilizing an anthracite porous bed, nano/PCMs and nano-coating on pipes, as shown in Fig. 13 (a, b). Their reason for using an anthracite bed was to raise the absorption of solar energy, with NPs used to enhance the thermal properties of PCM in addition to black paint. Nano-PCMs were filled in 12 copper pipes, with nano-paint applied to these pipes. The results showed that by using NPs of CuO and Al_2O_3 at 0.3 wt% with a CuO nano-coating, this improved solar still performance by 55.8% and 49.5%, respectively.

Shoeibi et al. [143] have also used nano-PCM along with porous media for solar desalination. Anthracite material and CuO-PCM as a nano/PCM were investigated in their study, with configurations shown in Fig. 14 (a, b, c, d). In their study, improvement in water output was enhanced by 41.94% using this comfiguration, as compared to a conventional system.

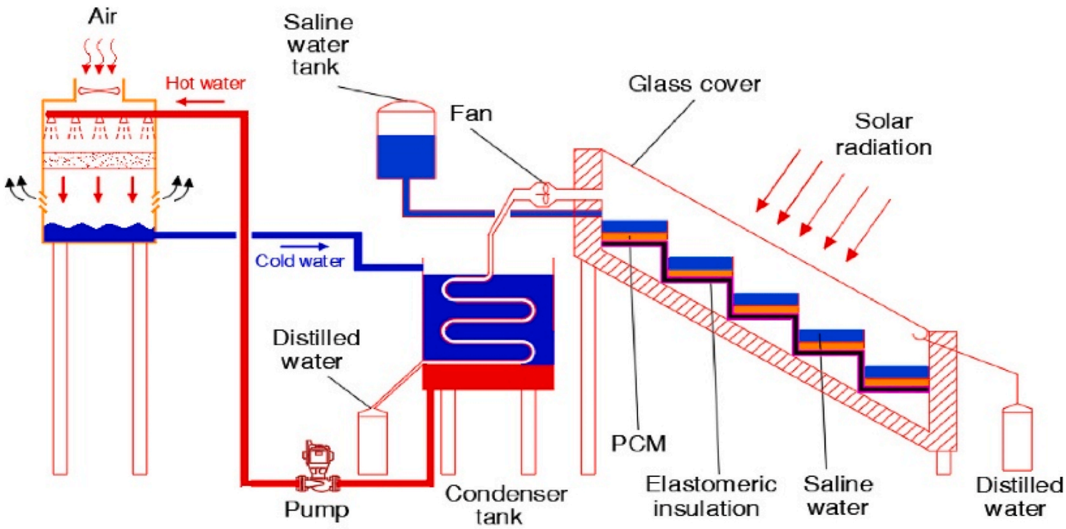
Abdullah et al. [144] have undertaken a study to enhance the performance of tray solar desalination with wick and nano-PCM. They used a corrugated tray solar still with wick material to cover the corrugations. CuO-PCM-based nano/PCM was also used to enhance performance of solar stills. The results showed that the total water production of the modified solar still was increased by 180% compared to the traditional system.

3.4. PCM-heat pipe-based solar desalination systems

Heat pipe (HP) is another very efficient method for increasing the rate of evaporation in solar desalination. As temperature rises in a HP evaporation section, the operating fluid evaporates and condenses on other side, by excahanging heat, whereby this cycle is repeated [145]. The thermal energy of the equipment increases the evaporation section temperature, and leads to evaporation of the working fluid in it, which is then transferred to the condenser section of the HP. Rastegar et al. [146] have utilized heat from a chimney, which was then supplied to solar desalination via a HP. In their study, a thermosyphon HP was applied to transfer the energy, where related photos and a sketch diagram are displayed in Fig. 15 (a, b). The efficiency with the HP configuration led to a 41% increment as compared to without the HP configuration.

Faegh and Shafii [147] have performed experiments with a solar still including PCM and a thermosyphon HP. On one side of their HP basin, water was used, whilst the other side was filled with PCM, as depicted in Fig. 16. The heat was transferred during the day by PCM and then during the night it was transferred using the HP. The authors concluded that water production was improved by 86% using this configuration in comparison to without the PCM and HP.

Behnam and Shafii [148] have conducted a study to measure the efficiency of HPs in an evacuated tube-based solar desalination system. A HP condenser was used to increase the water temperature, with results showing that performance was improved by 65%. Patel et al. [149] further measured the efficiency of triple basin solar stills by using an evacuated HP and energy storage material. Accordingly, the production of water using the evacuated tube HP and storage material was shown to be enhanced by 169%. Khalilmoghadam et al. [150] have used PCM with pulsating HPs in order to verify the output of a solar still. PCM was utilized during the day and energy was transferred to water during the night using the pulsating HP, as depicted in Fig. 17. Their results



(a)

(b)

Fig. 10. (a) Sketch diagram of proposed setup **(b)** Real experimental setup [122].

concluded that the production of water was 6.3 kg/ m^2/day using this novel configuration.

Various studies on PCM-HP-based solar desalination, as carried out by varied authors, are summarized in Table 3. Different authors have investigated various solar stills using HP with the aid of PCM, whereby they have improved water productivity. As is evident from viewing the table, a combination of heat pipe and phase change material has a positive influence on water generation by solar still.

4. Cost analysis of PCM-based solar desalination

Different factors should be taken into consideration when producing water using solar desalination. Manufacturing costs, running costs, capital recovery factor, and average annual water output are included factors, along with maintenance costs during running operations [154]. Capital recovery factor (CRF), fixed annual cost (FAC), sinking fund factor (SFF), annual salvage value (ASV), average annual water output (M), annual cost (AC), and S (Salvage value) are cost factors. Annual maintenance cost (AMC) and cost of distilled water per liter (CPL (Cost Per Liter)) can also be included in calculations as [155]:

$$\mathrm{CRF} = \mathrm{i}(1+\mathrm{i})^{\mathrm{n}} \Big/ \left[(1+\mathrm{i})^{\mathrm{n}-1}\right] \tag{20}$$

$$\mathrm{SFF} = \mathrm{i} \Big/ \left[(1+\mathrm{i})^{\mathrm{n}-1}\right] \tag{21}$$

$$\mathrm{ASC} = (\mathrm{SFF})\ \mathrm{S} \tag{22}$$

Where

$$\mathrm{S} = 0.2\mathrm{P} \tag{23}$$

$$\mathrm{AC} = \mathrm{FAC} + \mathrm{AMC} - \mathrm{ASV} \tag{24}$$

$$\mathrm{FAC} = \mathrm{P}(\mathrm{CRF}) \tag{25}$$

$$\mathrm{AMC} = 0.15\ \mathrm{FAC} \tag{26}$$

$$\mathrm{CPL} = \mathrm{AC}/\mathrm{M} \tag{27}$$

where P = present capital cost of unit; i = interest per year; and n = years.

Kabeel et al. [156] have conducted a numerical study to compare

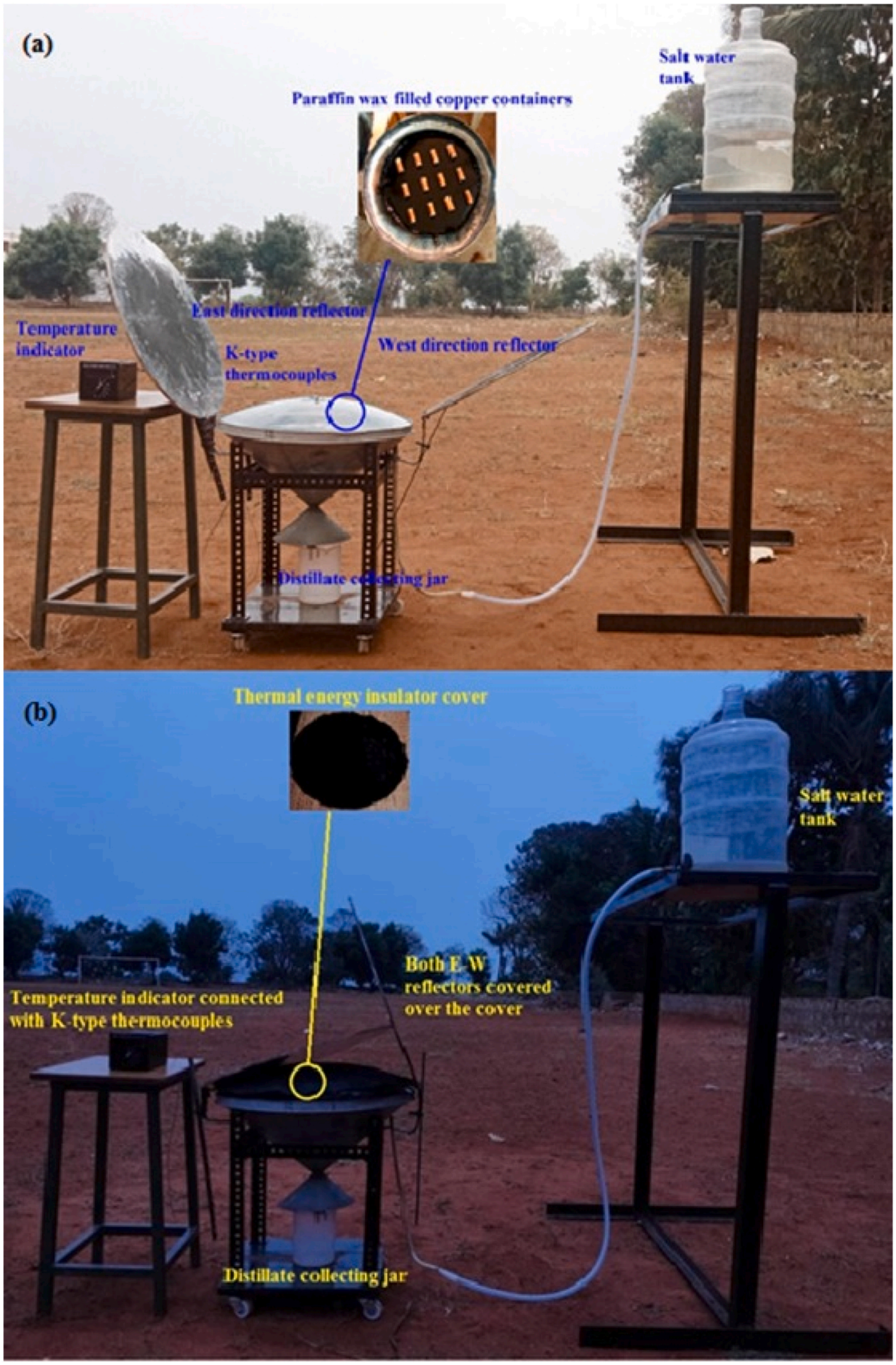


Fig. 11. Real experimental setup **(a)** tabular solar still with mirrors and energy storage during daytime **(b)** with mirrors, energy storage and insulation during nocturnal period [126].

various PCMs, with a focus on productivity, return period and economic analysis. Eight organic and three inorganic PCMs were utilized in the study, where the solar still lifetime was 10 and 40 years, with an interest rate of 16%. Their results showed that A48 organic PCM incurred a minimum productivity cost with the highest water output, as illustrated in Fig. 18 (a, b). The capric-palmitic based PCM indicated the lowest cost among all used PCMs, as depicted in Fig. 18 (c, d).

A summary of various studies completed on cost analysis using PCM-based solar stills is summarized in Table 4. Different authors have investigated various solar stills with the aid of PCM and measured water productivity costs. The obtained outcomes of these studies show that the lowest CPL of the solar desalination system can be achieved by tubular solar desalination using nano/PCM, costing apprxoimatelt $/L 0.0165.

5. 5 Environmental evaluation of PCM-based solar desalination based on energy

Environmental assessments, such as CO_2 emission mitigation based on energy and exergy, play a significant role on the design of solar desalination. To maximise CO_2 emission mitigation, a high water production rate is required. The annual energy and exergy production for this system can be derived by Ref. [158]:

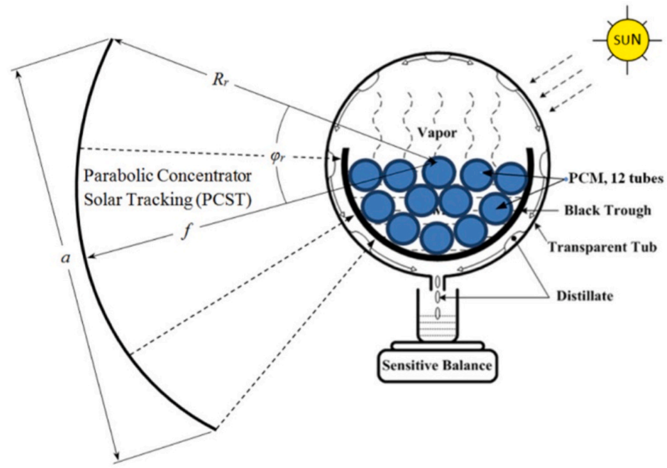


Fig. 12. Conventional solar still having parabolic concentrator solar tracking [127].

$$(E_{en})_{out} = \frac{M \times h_{fg}}{3600} \tag{28}$$

$$(E_{ex})_{out} = \frac{M \times h_{fg}}{3600}\left(1 - \frac{T_a}{T_w}\right) \tag{29}$$

where M is the annual water generation by solar desalination using PCM.

5.1. CO_2 removal

The annual CO_2 emission mitigation in a solar still is approximately $(E_{en})_{out} \times 2$ [161]. Therefore, CO_2 emission removal during the lifespan of the system can be calculated by $(E_{en})_{out} \times 2 \times n$ [161]. The net content of CO_2 emission removal during a device's lifespan is the lifespan energy generation by the system excluding the embodied energy, which is calculated by Ref. [162]:

$$G_{co_2} = \frac{2\,((E_{en})_{out} \times n - E_{in})}{1000} \tag{30}$$

where E_{in} shows the embodied energy (the energy needed for the production of the components).

5.2. Exergoenvironmental analysis

Whilst freshwater generation requires energy consumption using fossil fuels that pollute the environment, solar-sourced energy can decrease this pollution. Accordingly, exergoenvironmental analysis is considered to reduce CO_2 removal based on exergy generation by the system. The exergoenvironmental parameter is calculated by Ref. [163]:

$$G_{ex,co_2} = \frac{2\,((E_{ex})_{out} \times n - E_{in})}{1000} \tag{31}$$

The cumulative CO_2 emission removal of a solar desalination system can be obtained by the sum of CO_2 emission removal based on exergy and energy and is given by Ref. [164]:

$$G_{total} = G_{ex,co_2} + G_{co_2} \tag{32}$$

The advanced energy material assists to enhance the production of water using PCMs by storing thermal energy during the day, and utilizing it during the night. By selecting the lowest energy production for components in solar desalination, a system can achieve high CO_2 removal. Table 5 presents the total carbon dioxide removal of a solar desalination system using thermal storage media. The results indicate that by increasing generated freshwater of the device, total CO_2 removal by the system increases, which in turn assists to decrease pollution of the environment. Moreover, the total CO_2 removal of solar desalination using CuO nano-PCM and nano-coated techniques decreases carbon dioxide by about 12.03 tons during its lifespan [54].

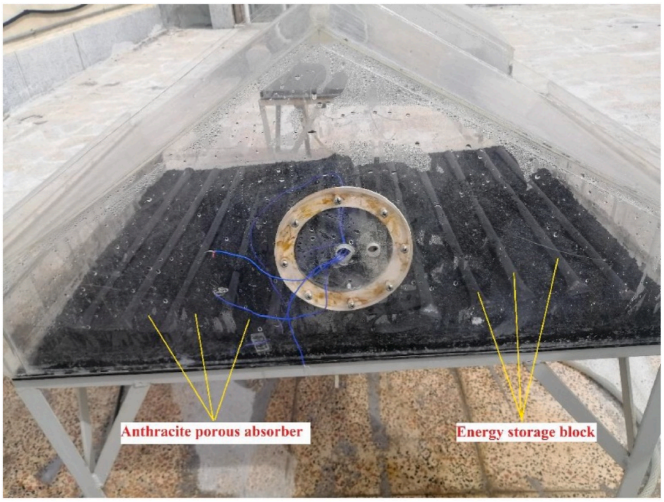
5.3. Energy analysis

The thermal efficiency of a system is defined by the ratio of production rate (outlet energy) to the sum of inlet energy from solar irradiance and other used energy in solar desalination. The daily thermal efficiency of a solar still can be calculated by Ref. [168]:

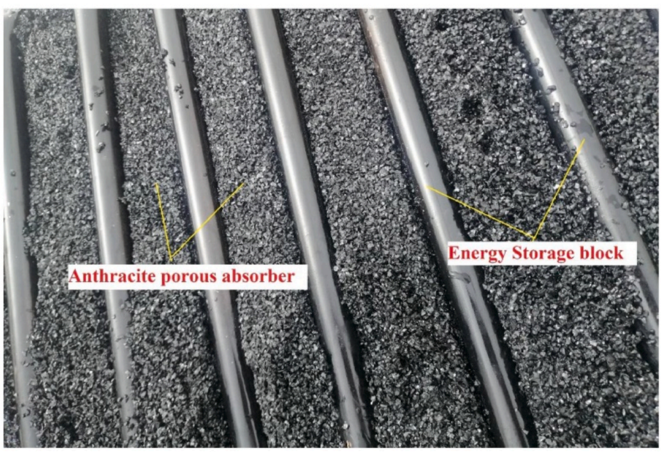
$$\eta_{daily} = \frac{\dot{m}_{ev} h_{fg}}{I_t A_b + \dot{W}_{Equipment}} \tag{33}$$

Table 2
Various studies done on PCM-based active solar desalination.

Type of study	Type of solar still	Location	PCM material	PCM enhancement	Maximum yield	References
Experimental	Solar still with CPC	Tanta, Egypt	Paraffin wax	Graphite NPs	9.81 L/ m^2/day	[130]
Experimental	Stepped solar still with evacuated tube collector	Tanta University Egypt	Paraffin	Graphite plates	13.62 L/ m^2/day	[131]
Experimental	Solar still integrated with solar collector	Borg Al-Arab city, Egypt.	black steel wool fibers	–	3.534 kg/ m^2/day	[132]
Experimental and Numerical	Double slope solar still with solar collector	Hefei, China	Shape stabilized PCM of paraffin wax polyethylene	–	1000 L/ m^2/year	[133]
Experimental	double slope solar still with internal sidewall reflector and circular fins	Rajshahi, Bangladesh	Paraffin wax	Al2O3 nanoparticle	1853 mL/day	[134]
Experimental	Solar still with parabolic dish concentrator and condensing unit	Jodhpur, India	Paraffin wax	–	7.12 L/day	[135]
Numerical	Multi-stage desalination unit with flat plate solar collectors	Yazd, Iran	Stearic acid	–	379.6 kg/ m^2/day	[136]
Experimental	Heat pump assisted regenerative solar still	Coimbatore, India	Slack wax	–	16.5 kg/ m^2 in 12 h	[137]
Experimental	Solar still coupled with evacuated solar collector and ultrasonic humidifier	Alexandria, Egypt	Paraffin wax	–	7.4 kg/ m^2/day	[138]
Experimental	heat pump water heater assisted regenerative solar still	Coimbatore city, India	Paraffin wax	–	16.1 kg/ m^2/day	[139]
Experimental	Solar still coupled with two parabolic concentrators	Ismailia, Egypt	Paraffin wax	–	11.1 L/ m^2 day	[140]
Numerical	Double-slope solar still equipped with photovoltaic thermal collector	Zahedan, Iran	Paraffin wax	–	6.5 kg/ m^2/h	[141]



a)



b)

Fig. 13. (a) Double slope solar still **(b)** porous media having energy storage material [142].

where $\dot{W}_{Equipment}$ presents the power consumption of other sources of energy, where in conventional solar stills this is equal to zero.

5.4. Exergy analysis

The exergy efficiency is specified by dividing the exergy generated by a system to the total inlet exergy to solar desalination, and is obtained by Ref. [169]:

$$\eta_{Ex} = \frac{Ex_{Product}}{Ex_{input}} \tag{34}$$

The inlet exergy and exergy generated by solar desalination are given by Ref. [170]:

$$\mathbf{EX_{in}} = \mathbf{I_t A_b} \times \left[\mathbf{1} - \frac{\mathbf{4T_a}}{\mathbf{3T_s}} + \frac{\mathbf{1}}{\mathbf{3}} \left(\frac{\mathbf{T_a}}{\mathbf{T_s}} \right)^{\mathbf{4}} \right] + \dot{\mathbf{W}}_{\mathbf{Equipment}} \tag{35}$$

$$\mathbf{EX_{product}} = \frac{\dot{\mathbf{m}}_{\mathbf{ev}}}{\mathbf{3600}} \times \mathbf{h_{fg}} \times \left(\mathbf{1} - \frac{\mathbf{T_a}}{\mathbf{T_w}} \right) \tag{36}$$

5.5. Energy payback time

The energy payback time is defined by the value of time that energy or exergy produced by solar desalination takes to attain the energy utilized to generate the goods of a solar still, and is obtained by Ref. [171]:

$$\mathbf{EPBT_{En}} = \frac{\mathbf{E_{in}}}{(\mathbf{E_{en}})_{\mathbf{out}}} \tag{37}$$

$$\mathbf{EPBT_{Ex}} = \frac{\mathbf{E_{in}}}{(\mathbf{E_{ex}})_{\mathbf{out}}} \tag{38}$$

where E_{in}, $(E_{ex})_{out}$ and $(E_{en})_{out}$ present embodied energy, yearly energy and exergy produced by a system, respectively.

5.6. Energy product factor

Energy efficiency factor is specified as the ratio of yearly energy and exergy generated by a system to the embodied energy of solar desalination, and is calculated by following formula [172,173]:

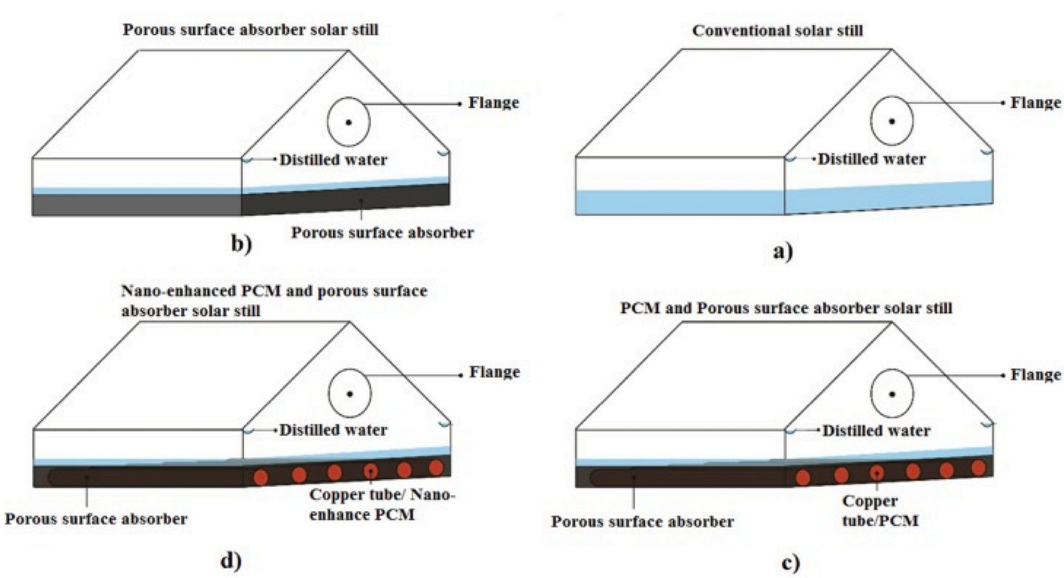
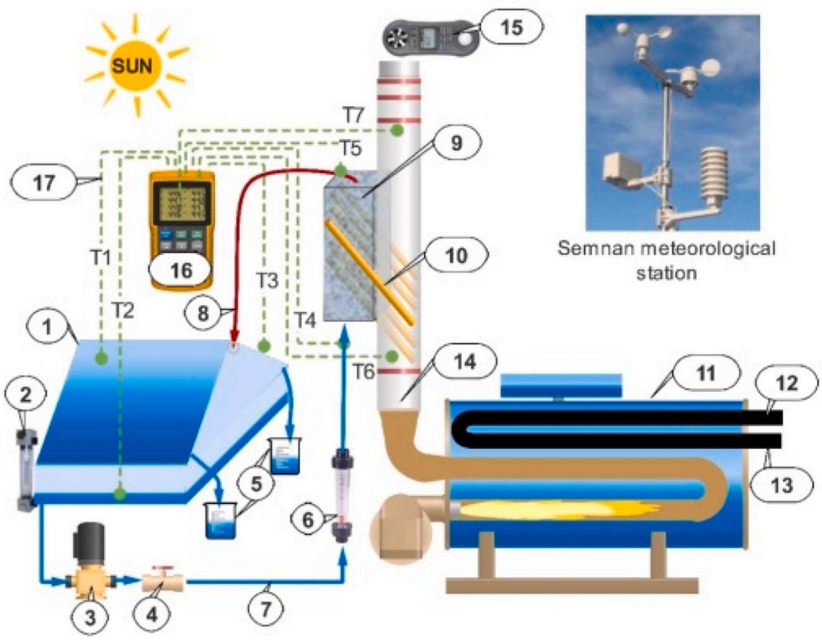


Fig. 14. Different solar still having **(a)** Conventional **(b)** Porous absorber **(c)** PCM with porous media **(d)** Nano-PCM with porous media [143].

(a) A photographic image



(b) Schematic diagram: 1) double slope solar still, 2) graded sight glass, 3) pump, 4) valve, 5) graduated beaker, 6)rotameter, 7) cold water, 8) preheated water (multilayer pipe), 9)thermosyphon heat pipe heat exchanger, 10)THP ,11) heater, 12) inlet gas, 13) outlet gas, 14) exhaust pipe(stack), 15)anemometer,16) data logger, 17) K type thermocouples

Fig. 15. (a) Experimental setup with heat pipe **(b)** Schematic diagram of setup [146].

$$\mathbf{EPF_{En}} = \frac{(\mathbf{E_{en}})_{\mathbf{out}}}{\mathbf{E_{in}}} \tag{39}$$

$$\mathbf{EPF_{Ex}} = \frac{(\mathbf{E_{ex}})_{\mathbf{out}}}{\mathbf{E_{in}}} \tag{40}$$

5.7. Exergoeconomic analysis

Exergoeconomic evaluation is the couple of cost and exergy assessment at the same time considered for the cost effective design of a system. Exergoeconomic evaluation is defined as the ratio of yearly energy and exergy generated to uniform yearly cost of solar desalination, and is calculated by Refs. [174,175]:

$$\mathbf{R_{Ex}} = \frac{(\mathbf{E_{ex}})_{\mathbf{out}}}{\mathbf{UAC}} \tag{41}$$

$$\mathbf{R_{En}} = \frac{(\mathbf{E_{en}})_{\mathbf{out}}}{\mathbf{UAC}} \tag{42}$$

Table 6 depicts exergoeconomic, energy payback time and energy production factor parameters based on energy and exergy of a solar desalination system using advanced energy media. The results show exergoeconomic parameters based on energy to always be more than exergoeconomic energy based on exergy, due to highest energy output

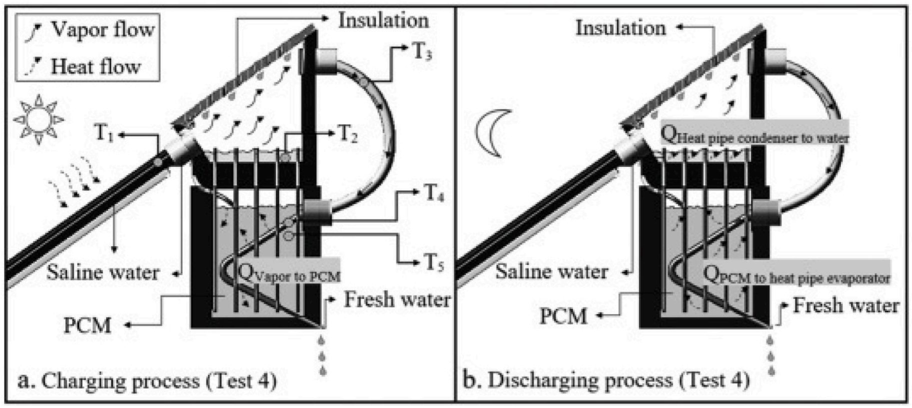


Fig. 16. Sketch view of solar still with HP [147].

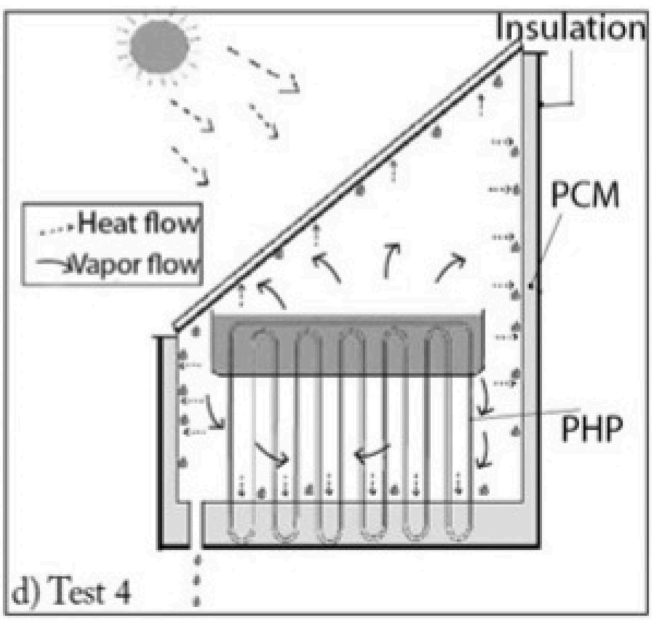


Fig. 17. Solar desalination having PCM and pulsating heat pipe [150].

compared to exergy output of a system. Further, energy payback time based on energy of solar desalination using CuO and TiO_2 nanofluids was about 1.10 and 1.043 years, respectively. Moreover, it could be seen that the use of nano-enhanced PCM had a direct effect on energy payback time and exergoeconomic parameters of solar desalination.

Tables 1–3 represent studies that have been conducted to illustrate water productivity using different absorber materials in solar desalination. The investigated energy storage materials are paraffin wax, salt hydrates, various fatty acids, shape-stabilized phase change materials, as well as steric acid used in different types of solar stills.

A comparison chart showing various energy storage materials used by different authors in their experimental studies, and their amount of water production, is represented in Fig. 19. Most of the studies' results indicate water production to be between 4 and 8 L/m^2/day. A pyramid solar still with paraffin wax as its phase change material produced 8.1 L/m^2/day. Therefore, the efficiency of solar stills using energy storage materials can be increased, which can enhance water productivity.

The evaporation rate of a solar still is a vital factor that indicates the amount of water production produced by a solar still. The evaporation rate largely depends upon the geometry of the solar still, which may enhance its amount of water production. The more nucleation sites on the water surface, the more water will be produced in terms of evaporation rate. Factors including incident solar radiation on the surface of a solar still, energy storage material and geometry of a solar still can help in determining the amount of water production. Energy storage materials indicate how much energy can be stored in them, which can later help in creating more volume of water. As evident in the graph in Fig. 20 below, authors have used solar stills integrated with CPC with paraffin as its energy storage material, resulting in a high amount of water production. Measeurments indicated a maximum of 11.1 L/m^2/day and the average evaporation rate in the case of an active solar still was around 3.5–6.5 L/m^2/day. The type of solar system integrated with solar still largely affect the amount of water produced by a solar still.

The rate of evaporation also depends upon the type of porous materials or heat pipe used along with PCMs in a solar still. As evident in Tables 3 and it is clear that the use of HPs along with energy storage materials can further enhance water productivity of a solar still. The maximum amount of water was produced by thermosyphon HP, having

Table 3
Various studies done on PCM and heat pipe on solar desalination.

Type of solar still	Type of Heat pipe	PCM material	Water productivity	Results	References
Solar still	Thermosyphon heat pipe based evacuated solar collector	Paraffin wax	$6.555\ \frac{kg^2}{m}/day$	Water production was improved by 86% compared to the system having no PCM.	[147]
Triple-basin solar still	Evacuated HP solar collector	Pebbles, granite gravel	$19\ \frac{kg^2}{m}/day$	Water production by evacuated tube HP along storage media was enhanced by 169%.	[149]
Novel designed single effect solar still	Pulsating HP	Paraffin wax	$6.3\ \frac{kg^2}{m}/day$	The increase in efficiency was from 23.7% to 48.5% in the case of current configuration.	[150]
Single effect solar still	Evacuated tube based thermosyphon HP	None	$1.02\ \frac{kg^2}{m}/h$	Results indicated that efficiency using this system was 22.9%.	[151]
Pyramid solar still	Thermosyphon HP having solar collector	None	$6970\ \frac{mL^2}{m}/day$	System performance having ethanol in HP was increased by 26%.	[152]
Solar still	Evacuated tube HP solar collector	None	$1190\ \frac{L^2}{m}/year$	Water production using an evacuated tube HP was 2.13 times higher than conventional one.	[153]

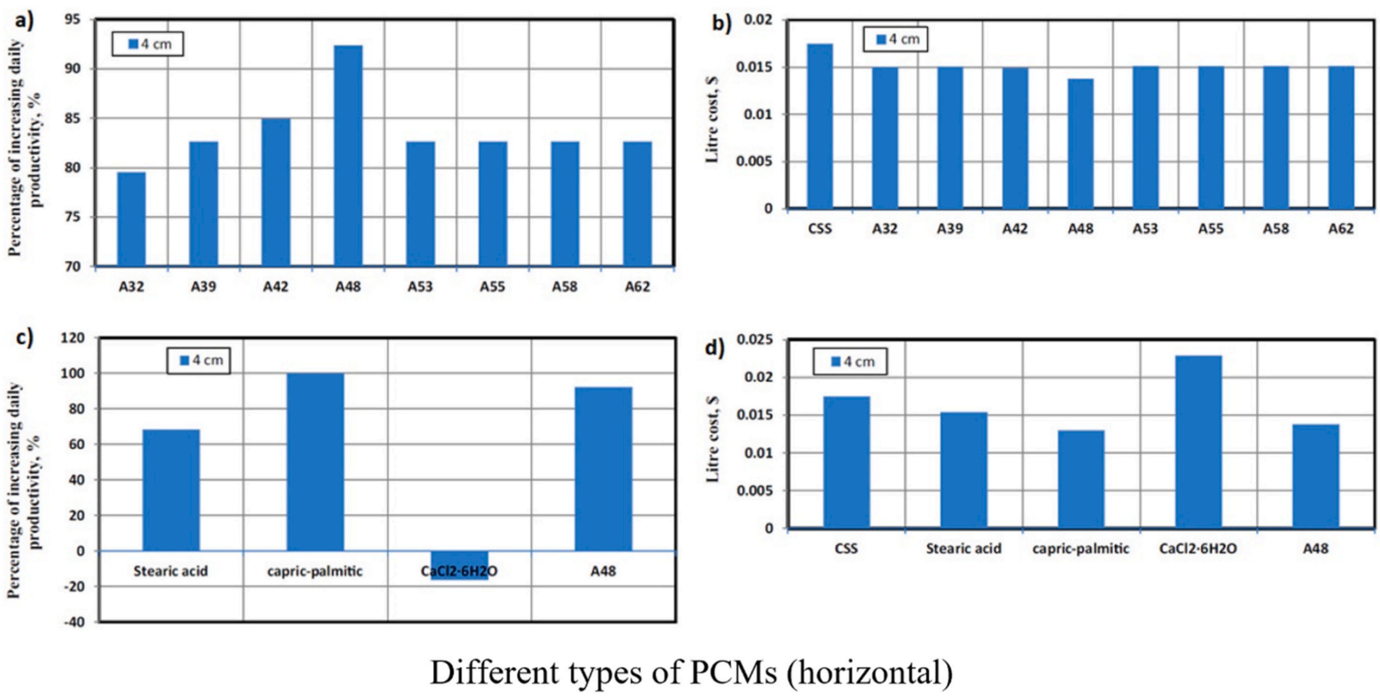


Fig. 18. (a) water productivity of organic PCMs **(b)** distillate water cost for organic PCMs **(c)** water productivity of inorganic PCMs **(d)** distillate water cost for inorganic PCMs [156].

Table 4
Various studies done on PCM-based solar desalination with respect to CPL.

Type of solar still	PCM material	Freshwater cost ($/liter)	Maximum yield (L/ m^2/day)	References
Tubular solar still using nano enhanced PCM	Paraffin wax with carbon black NPs	0.0164	–	[70]
Double-slope solar still having Nano-PCM	Paraffin wax with copper and alumina NPs	0.013	–	[142]
Solar still having PCM	Palmitic acid	0.019	4.9	[157]
Solar still having PCM, fins	Paraffin wax	3.78	0.0416	[158]
Solar still having PCM, steel fins	Paraffin wax	4.08	0.0343	[158]
Solar still having fins	None	0.023	2.81	[159]
Solar still having PCM	Paraffin wax	0.03	–	[160]

a solar collector combined with solar stills, measured at 6.9 L/m^2/day.

Various authors have compiled studies on PCM-based solar desalination with respect to CO_2 mitigation, as depicted in Table 4. Accordingly, various energy storage materials have been applied by various authors, whereby time span and CO_2 mitigation were determined. These were in the range of 10–30 years and 3.05–28.83 ton/lifespan respectively, as shown in Fig. 21. It can be concluded from this figure that PCM based solar stills have the maximum CO_2 mitigations as compared to other solar stills using different materials. Therefore, it can be concluded that PCM based solar stills have a higher life span and better CO_2 mitigation.

6. Thermal modelling and sensitivity analysis for solar still by incorporating energy storage materials

6.1. Thermal modelling

Thermodynamic analysis can reduce construction costs and optimize the generated water of solar desalination systems using energy storage materials. One of the significant problems of using energy storage materials to increase desalination efficiency is the lower time for receiving maximum thermal energy from the sun during the day. In. this way, energy storage materials absorb the thermal energy of the sun and transfer it to a system when it is needed, acting like a thermal battery. The higher the amount of energy storage media, the more heat is stores during the day, which in turn decreases the thermal efficiency of the system. The lower amount of energy storage media, leads to lower energy storage in the system, whereby the performance of solar desalination reduces significantly at the required time. Therefore, the optimal amount of energy storage materials posses has a great impact on water output in a solar desalination system. Various authors have conducted thermal modelling of solar stills using energy storage materials within the literature. Tuly et al. [109] have conducted an experimental study on double slope solar stills that consist of fins, PCM, external condenser, and wick material for performing energy, exergy, economic, exergo-economic, exergo-environmental, and sustainability analysis. The results revealed that the solar still with all the above mentioned modifications gained the highest efficiency of 32.46%, with daily water productivity of 2.28 L/m^2. Agwal and Singh [181] have used organic PCMs and performed experimental and computational modelling of double slope solar stills. ANSYS FLUENT 19.2 workbench was used to create a multiphase 3-D CFD model of the solar still. The results of combining two organic PCMs increased thermo-physical properties of PCM and improved the overall performance of the system.

Soner et al. [68] have used an artificial neural network model to measure thermal efficiency and water yield of tubular solar stills. The modified solar still was evaluated based on energy and exergy efficiency. The results concluded that performance was optimized using an artificial neural network. Sonware et al. [182] have studied a single slope

Table 5
Different studies performed on PCM-based solar desalination with respect to CO_2 mitigation.

Energy storage material	Location	Maximum yield (L/m^{2}day)	Lifespan (years)	Total CO2 removal (Ton/lifespan)	References
Sensible heat storage (Water depth of 1 cm)	Coimbatore, India	842	10	8.27	[68]
Sensible heat storage (Water depth of 3 cm)	Coimbatore, India	602	10	5.75	[68]
Phase change material	Alexandria, Egypt	722	30	28.83	[69]
Conventional solar desalination with porous media	Tehran, Iran	368	20	9.49	[142]
Solar still with PCM	Tehran, Iran	395	20	9.06	[142]
Solar still with PCM and nano-coated (10 wt% CuO nano powders added in black paint)	Tehran, Iran	407	20	9.39	[142]
Solar still with nano/PCM (0.1 wt% CuO) and nano-coated (10 wt% CuO nano powders added in black paint)	Tehran, Iran	462	20	10.95	[142]
Solar desalination with nano/PCM (0.3 wt% CuO) and nano-coated (10 wt% CuO nano powders added in black paint)	Tehran, Iran	505	20	12.03	[142]
Solar desalination with nano/PCM (0.1 wt% Al_2O_3) and nano-coated (10 wt % CuO nano powders added in black paint)	Tehran, Iran	446	20	10.5	[142]
Solar desalination with nano/PCM (0.1 wt% Al_2O_3) and nano-coated (10 wt % CuO nano powders added in black paint)	Tehran, Iran	484	20	11.57	[142]
Solar still by PCM thermoelectric heater	Tehran, Iran	10.8	20	11.87	[165]
Solar still by PCM thermoelectric heater	Tehran, Iran	10.8	30	20.05	[165]
Solar still by PCM thermoelectric cooler	Tehran, Iran	6.04	20	4.66	[165]
Solar still by PCM thermoelectric cooler	Tehran, Iran	6.04	30	9.23	[165]
Drum solar still using paraffin-Ag nano/PCM	Kafrelsheikh, Egypt	2.85	20	14	[166]
Double slope solar still using reflector, fin and PCM	Bangladesh	615	20	3.04	[167]
Double slope solar still using reflector, fin and nano/PCM	Bangladesh	704	20	3.65	[167]

solar desalination unit using computational fluid dynamics via COMSOL Multiphysics software, whereby the absorptivity of water using absorbing materials was investigated. The results indicated that exergy, evaporation, and heat transfer coefficient increased by 10.52%, 13.68% and 5.37%, respectively. Modi et al. [183] have enhanced the productivity of a single-basin dual-slope solar still by adding hollow-fins and wick-segments. Enhancements of 5.20% and 9.39% in efficiency was obtained from the solar stills with partially submerged hollow-fins and wick-segments, respectively. Sharshir et al. [184] have used wick solar stills using an artificial neural network integrated with tree–seed algorithm to determine freshwater production. The results concluded that the productivity of water increased by about 50% compared to the conventional wick solar still when using this configuration.

Negi et al. [185] have explored the utilization of PCMs in both active and passive solar stills for enhancing thermal efficiency and productivity. Their study involved the evaluation of experimental studies utilizing PCMs, including an analysis of exergy performance of solar stills. The authors noted that the choice of PCMs was affected by factors such as location, availability and thermophysical features. Additionally, the author recommended the use of a solar still equipped with a parabolic concentrator type collector, with spiral tubes as a means of augmenting the overall productivity of the solar still. Chhabra et al. [186] have discussed a variety of solar still shapes, including double slope, tubular, pyramid and weir-type cascade, along with design modifications such as the inclusion of parabolic concentrators, evacuated tubular collectors, v-corrugated absorber plates and corrugated wicks in solar stills. The use of PCMs and nanofluids for enhancing the efficiency of solar stills were also considered. The evacuated tube collector-based solar still was noted to yield notable outcomes, whereby the utilization of PCMs facilitated the yield during off sunshine periods, and multiple nanoparticles exhibited their potential to enhance productivity of solar stills.

Purnachandrakumar et al. [187] have conducted an extensive review of the significance of utilizing CFD tools for analyzing, gauging performance and optimizing the design of solar stills. The authors discussed various modeling techniques, their underlying assumptions and the governing equations for each approach. CFD simulations may provided accurate predictions solely based on the input of prevailing atmospheric conditions and solar radiations. The important results from the CFD studies were summarized, and the studies were sorted into groups based on configurations, computational domains, operational parametric ranges and geometrical parametric ranges. Singh et al. [188] have reviewed the exergoeconomic and enviroeconomic parameters associated with a basin-type single slope solar still incorporating nanofluids. The performance of a single slope solar still improved with the addition of a water-based nanofluid. Furthermore, it was recommended to use an active double slope solar still instead of a passive single slope solar still for better water productivity. Patel et al. [189] have conducted a critical study of different shapes of basin liners, including solar stills with fins, corrugated wick, hemispherical basin, cascaded, and stepped stills. The findings showed that the corrugated wick solar still yielded the highest output due to its increased evaporation surface area. Solar stills with semicircular corrugated wicks offered a higher yield than flat corrugated wicks, while solar still with hollow fins a circular cross-section outperformed square cross-section fins. The yield of cascade solar stills was varied by water flow, as the yield of such solar stills decreased as the flow of water increased and vice versa.

Singh et al. [190] have examined the impact of nanofluid addition on the thermal efficiency of various types of solar collector based solar stills. The investigation focused on the use of nanofluids containing carbon, aluminum oxides, titanium oxide, silver, copper oxide and other similar materials. The findings of various research studies have shown that the incorporation of nanofluids in solar stills caused a notable enhancement in thermal output. This can be attributed to the heightened heat transfer rate of nanofluids in comparison to pristine fluids. Singh et al. [191] have completed a review of a double slope solar still with a basin type design, with and without the use of nanofluid. Their analysis was focused on exergoeconomic and enviroeconomic parameters. The study revealed that the incorporation of nanofluids had a positive impact on the operational efficacy of a solar still. Furthermore, it was suggested that a active solar still presented superior efficiency when compared to a passive solar still.

Singh et al. [192] have explored the thermal modeling of solar stills packed with and without nanofluids. The integration of nanofluids within a solar still system led to a significant increase of a system's output. Additionally, an active single slope solar still with nanofluid base fluid induced better performance than conventional solar stills. The

Table 6
Various studies performed on advance energy-based solar desalination with respect to exergoeconomic, EPBT and EPF.

Energy storage material	Location	Exergoeconomic based on energy (kWh/$)	Exergoeconomic based on exergy (kWh/$)	EPBT	EPF	References
Paraffin wax as a PCM	Alexandria, Egypt	96.9	5.6	1.6 (based on energy) 27.9 (based on exergy)		[176]
Jute wick in basin (Water depth of 1 cm)	Allahabad, India		2.35	0.692 (based on energy) 13.24 (based on exergy)	1.44 (based on energy) 0.075 (based on energy)	[177]
Black cotton wick in basin (Water depth of 1 cm)	Allahabad, India		2.97	0.637 (based on energy) 10.6 (based on exergy)	1.56 (based on energy) 0.094 (based on energy)	[177]
Al_2O_3/Water nanofluid	Pune, India		0.74	0.982 (based on energy) 12.11 (based on exergy)	10.17 (based on energy) 0.825 (based on exergy)	[177]
TiO_2/Water nanofluid	Pune, India		0.57	1.043 (based on energy) 13.28 (based on exergy)	9.59 (based on energy) 0.752 (based on exergy)	[178]
CuO/Water nanofluid	Pune, India		0.39	1.103 (based on energy) 14.89 (based on exergy)	9.066 (based on energy) 0.067 (based on exergy)	[178]
PV/T(With heat exchanger)- Al_2O_3 nanofluid	New Delhi, India		3.43	2.35 (based on energy) 12.9 (based on exergy)	4.7 (based on energy) 0.6 (based on exergy	[179]
PV/T(With heat exchanger)- TiO_2 nanofluid	New Delhi, India		2.63	2.20 (based on energy) 11.9 (based on exergy)	4.6 (based on energy) 0.55 (based on exergy	[179]
PV/T(With heat exchanger)- CuO nanofluid	New Delhi, India		2.36	2.1 (based on energy) 10.6 (based on exergy)	4.8 (based on energy) 0.65 (based on exergy	[179]
Tubular solar desalination with Al_2O_3 nanofluid cover cooling	Iran	16.85	0.98			[180]
Paraffin wax	Iran	5.82	0.64	1.39 (based on energy) 12.65 (based on exergy)		[180]
Nano-enhanced PCM (Paraffin/0.2% CuO)	Iran	6.52	0.72	1.24 (based on energy) 11.3 (based on exergy)		[143]

use of film cooling in a solar still yielded better outcomes when compared to the implementation of flood cooling. The enhanced performance of solar stills can be attributed to the compatibility and optimum concentration of nanoparticles.

Dharamveer et al. [193] have reviewed the utilization of nanofluids in both active and passive solar stills. The integration of a heat exchanger and nanofluid in an active solar still provided better performance compared to an active single slope solar still with an external condenser. The usage of nanofluid resulted in an increase in water yield, owing to the enhanced thermal conductivity and absorptivity of the nanofluid. Moreover, internal paint color influenced the heat absorption and; hence, affected solar still performance. The employment of film cooling was noted to be a more favorable choice in comparison to flood cooling. Singh et al. [194] have conducted a comprehensive analysis on the application of nanofluids in solar desalination systems. Research findings showed that incorporating nanofluid into solar stills effectively enhanced productivity due to their favorable thermo-physical and optical properties. The addition of flake nanoparticles, phase change material (PCM), and film cooling in an active solar still resulted in superior performance compared to an active single slope solar still equipped with an external condenser. Additionally, the employment of black-colored still basins and film cooling were recommended for enhancing the efficiency of a solar still.

6.2. Sensitivity analysis

Sensitivity analysis has been widely used to optimize the performance of solar desalination systems [195–198]. The sensitivity analysis of performance parameters in a single-slope solar desalination system was numerically examined by Mohsenzadeh et al. [186]. The aspect ratio of the evaporation rate in the enclosure, the heat energy inertia of each component, and the concentration of saline water were considered in the model of the system. The range of 10% of solar irradiation, wind velocity and surrounding temperature parameters were assessed. The results indicated that the daily water generation and energy efficiency of the solar desalination were about 2.52 L/m^2 and 19.2%, respectively. Chen and Xie [199] evaluated the performance of tubular solar desalination by vacuum pump and solar collector. The vacuum was applied in different stages of the solar desalination system, and water was recycled between the first stage of the solar desalination and solar collector. The outcomes revealed that the highest water generation of solar desalination was obtained at a working pressure of 48 kPa, which was about 19% more than solar still with nominal pressure. In another other study, Raturi et al. [200] have assessed the effects of N-evacuated tube solar

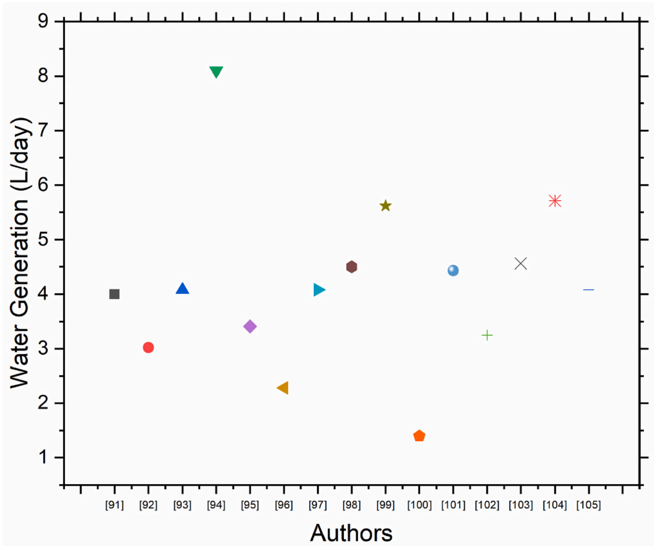


Fig. 19. Water productivity produced with passive solar still by various authors.

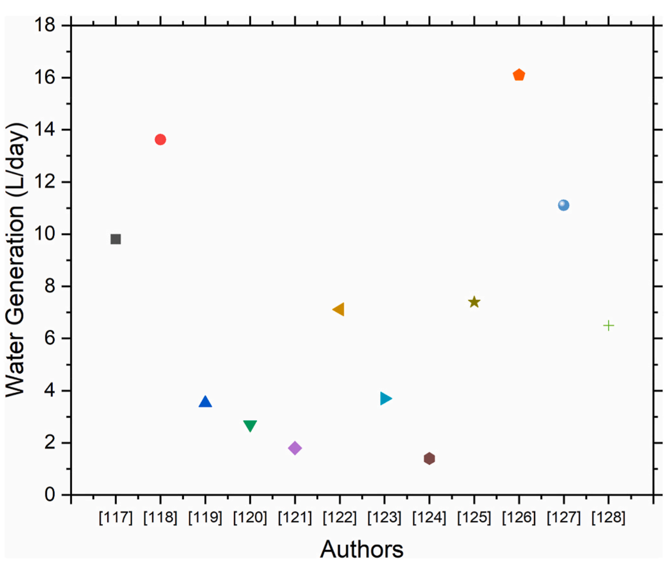


Fig. 20. Water productivity produced with active solar still by various authors.

collector on the performance of solar still by sensitivity analysis. The outcomes implied that the exergy gain was to be the most sensitive with regards to N having mean sensitivity figure amounts as 0.74 and 1.31, in that order. The sensitivity analysis can be used in numerical studies for finding the highest water productivity and thermal efficiency of the solar desalination system by future researchers.

7. Current status of solar desalination with energy storage materials

Advanced energy storage materials possess much better properties in terms of transfer of heat as compared to conventional materials. Hence, investigations in this area have grown considerably, as indicated by the number of studies in the last five years (2018–2022), as presented in Fig. 22, which have been taken from "Web of Science", using keywords of "advanced energy storage materials" and "desalination". The foremost researcher was "Ravish Ankar", who compiled studies on advanced energy storage materials in desalination. The second most prominent was "Abd Elnaby Kabeel" who has published several articles related to

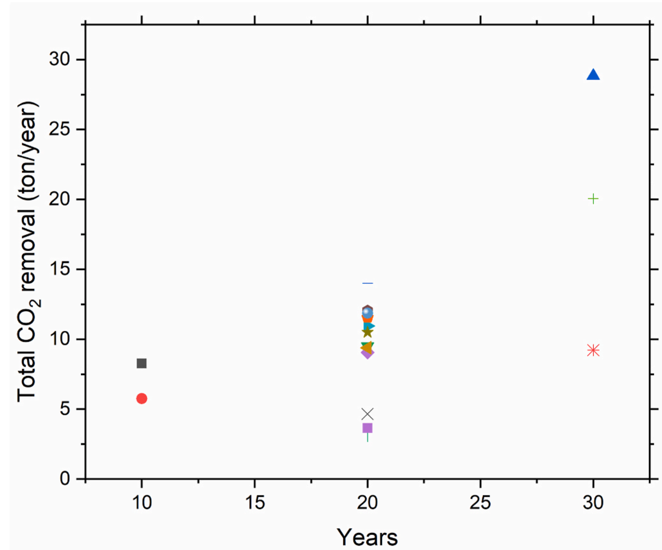


Fig. 21. Total CO_2 removal in years by various authors.

this area. China is the number one country engaging in this form of research, while Malaysia is last, as shown in statistics in Fig. 22. The foremost journal that has published the highest number of articles in this area is "Journal of Energy Storage". Following this is the "Solar Energy Materials and Solar Cells" journal, which has published papers in this field. Therefore, it can be concluded that researchers globally are continuously seeking to further investigate and present findings in the area of solar desalination using advanced energy storage materials.

8. Discussion of future scope

Combining energy storage materials with solar desalination can increase the water production rate in solar desalination. The energy storage materials receive the thermal energy of the system and release it to the solar desalination when the water temperature is decreased during the night. The potential of thermal energy storage materials can lead to combination with different thermal energy devices and receive their waste heat energy, which then transfers the thermal energy into the saline water of the solar desalination. In some previous research, the cold side of the thermoelectric module was considered to reduce the glass cover of the solar desalination and the thermal energy of the hot sides of thermoelectric module was lost. In other energy applications, such as solar panels, it is better to cool down the photovoltaic surface for improving the power generation of the system. The receiving waste thermal energy of the PV on energy storage materials can store a high amount of thermal energy on it. Coupling energy storage materials with energy applications for storing the waste thermal energy can increase the water productivity of the solar desalination system. Therefore, one of the significant roles of the energy storage material is storing the waste heat energy and releasing it to a solar desalination unit. Further, to reduce the cost of water productivity and also increase the CO_2 mitigation of the solar desalination system, various energy storage biomaterials or low costs energy storage materials can be selected. Moreover, the mixing of the nanoparticles in the phase change materials to produce the nano-enhanced PCM causes the reduction of the time speed of removing and receiving the thermal energy to the system. It is better to utilize the low cost of PCM with a suitable melting point related to the solar desalination system and the low cost of the nanoparticles with high thermal properties to increase the high generated water and lowest CPL of the system.

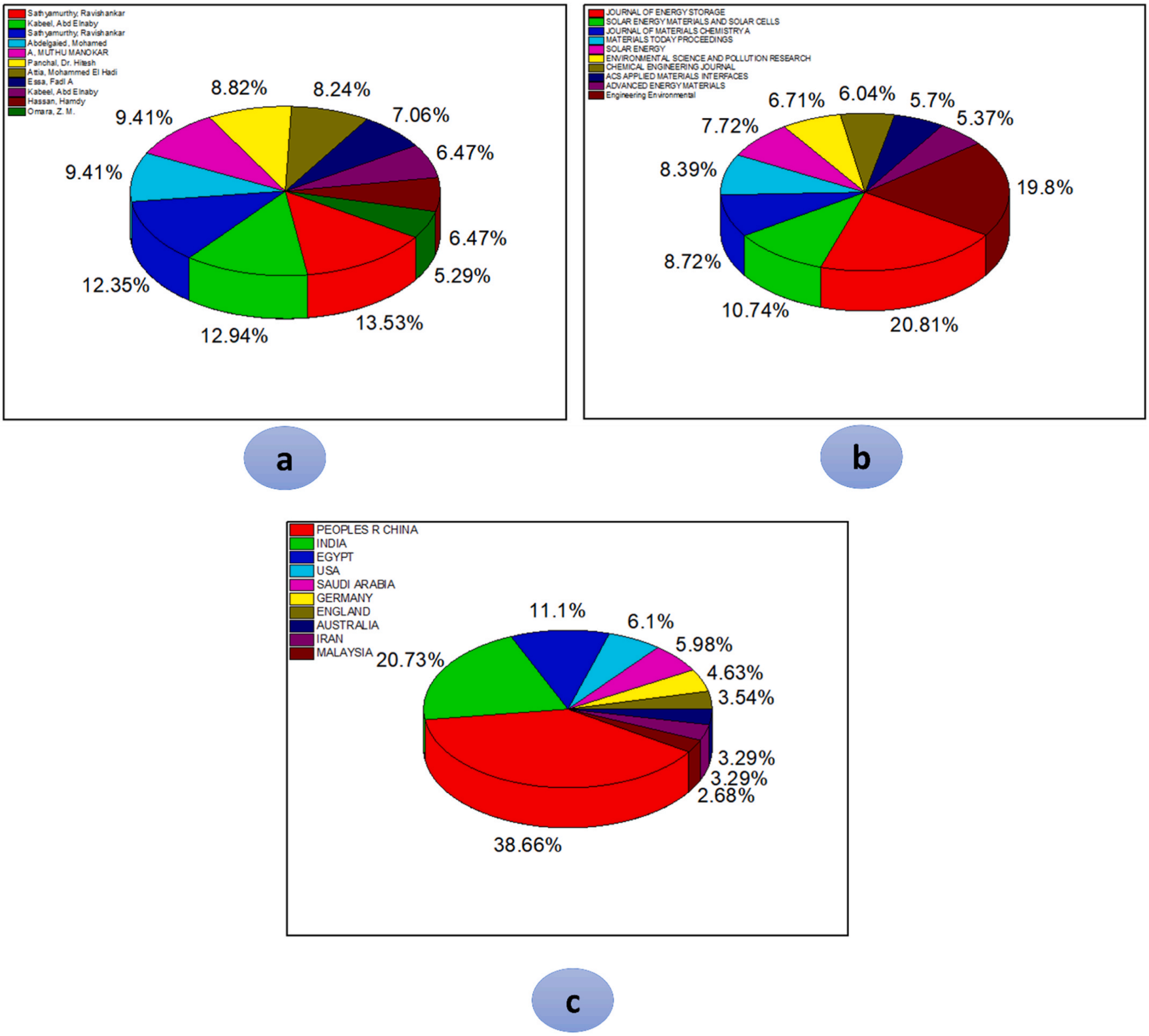


Fig. 22. Web of Science Stats having keywords "advanced energy storage materials" and "desalination" for 2018–2022 **(a)** authors **(b)** journals **(c)** countries.

9. Conclusions

Many people suffer from a lack of access to fresh water in remote areas. In these remote areas, where transport and pipelines are expensive, portable devices like solar stills are useful for the generation of water. Whilst water desalination plants do operate around the world, they are costly and may not fulfil all demands for fresh water. Accordingly, the efficient availability of fresh water is a demanding challenge that can be fulfilled by solar stills. Some of the major concluded points from this review are.

- The quantity of water produced by solar still is very low, but it can be improved by using nano materials for high productivity of water.
- The use of absorbing heat materials enhance solar still water productivity. Various advanced energy storage materials have been used to enhance the absorption of radiation in solar stills.
- Different nano PCMs and composite PCMs with fins can be utilized to increase the productivity of water. These advanced energy-storing materials are proven to improve water productivity of solar stills.
- The exergoeconomic parameter based on energy was always more than exergoeconomic based on exergy, due to the highest energy output compared to the exergy output of the system
- The current study also covers several types of active solar stills that include reflectors, solar parabolic concentrators, and photovoltaics with PCM. These types of solar stills have been shown to drastically increase the production of water.
- The productivity of solar stills can also be enhanced by utilizing PCM/porous materials, with results indicating solar still water productivity to be enhanced by 40–70 % via this combination.
- The energy payback time based on the energy of solar desalination using CuO and TiO_2 nanofluid was about 1.10 and 1.043 years, respectively.

- The use of thermosyphon heat pipes along with PCM enhance the water generation of solar stills, which increase water productivity by more than two times that of traditional solar stills.
- Cost analysis of PCM-based solar desalination shows that the performance of solar stills is much better. Also, the overall cost of water produced per liter is less than the conventional solar stills.
- By increasing the generated freshwater of the device, total CO_2 removal by the system increases and assists to decrease environmental pollution.
- Total CO_2 removal of the solar desalination using CuO nano/PCM and nano-coated decrease the carbon dioxide by about 12.03 tons during its lifespan.
- The use of nano-enhanced PCM had a direct effect on energy payback time and exergoeconomic parameters of solar desalination.

10. Recommendations for future work

Whilst the current review shows that many studies have been completed to increase the performance of solar desalination using advanced energy storage materials, further work should be completed in order to achieve improved results. Some future recommendations are.

- The combination of hybrid nanomaterials and fins with conventional solar still can be the subject of future studies as this is more efficient for water productivity. The same trend is applied to energy storage materials for improved solar still performance.
- The use of different and low-cost NPs on porous absorbers can improve the water output of solar stills.
- The combination of photovoltaic/thermal and heat pipes as waste heat of solar panels can be used for enhancement of water temperature in solar desalination. NPs can also be introduced for further enhancement in performance.
- In all the above discussions, only natural convection cases have been studied, where forced convection could be a new direction for future research into solar desalination.
- Economic and environmental analysis of low-price porous materials, as well as heat pipes, should be considered in future works as a means of ultimately decreasing the cost per liter of solar stills.
- Comparative study on the influence of the different energy storage materials on generated water of the various geometry of the solar desalination system.

Declaration of competing interest

Dear Editor, We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Data availability

Data will be made available on request.

References

[1] Khawaji AD, Kutubkhanah IK, Wie J-M. Advances in seawater desalination technologies. Desalination 2008;221:47–69.
[2] Shatat M, Riffat SB. Water desalination technologies utilizing conventional and renewable energy sources. Int J Low Carbon Technol 2014;9:1–19.
[3] Sathyamurthy R, Kabeel AE, Chamkha A, Kumar HA, Venkateswaran H, Manokar AM, et al. Exergy and energy analysis of a tubular solar still with and without fins: a comparative theoretical and experimental approach. Environ Sci Pollut Control Ser 2022;29:6612–21.
[4] Dhivagar R, Shoeibi S, Parsa SM, Hoseinzadeh S, Kargarsharifabad H, Khiadani M. Performance evaluation of solar still using energy storage biomaterial with porous surface: an experimental study and environmental analysis. Renew Energy 2023;206:879–89. https://doi.org/10.1016/j.renene.2023.02.097.
[5] Vaithilingam S, Muthu V, Athikesavan MM, Afzal A, Sathyamurthy R. Energy and exergy analysis of conventional acrylic solar still with and without copper fins. Environ Sci Pollut Control Ser 2022;29:6194–204.
[6] Negi A, Dhindsa GS, Sehgal SS. Experimental investigation on single basin tilted wick solar still integrated with flat plate collector. Mater Today Proc 2022;48:1439–46.
[7] Modi KV, Gamit AR. Investigation on performance of square pyramid solar still using nanofluid and thermal energy storage material: an experimental and theoretical study. J Clean Prod 2022;381:135115. https://doi.org/10.1016/j.jclepro.2022.135115.
[8] Mevada D, Panchal H, Ahmadein M, Zayed ME, Alsaleh NA, Djuansjah J, et al. Investigation and performance analysis of solar still with energy storage materials: an energy- exergy efficiency analysis. Case Stud Therm Eng 2022;29:101687. https://doi.org/10.1016/j.csite.2021.101687.
[9] Saxena A, Cuce E, Kabeel AE, Abdelgaied M, Goel V. A thermodynamic review on solar stills. Sol Energy 2022;237:377–413. https://doi.org/10.1016/j.solener.2022.04.001.
[10] El-Agouz SA, Abd Elbar AR, Aboghazala AM, Shahin M, Zakaria MY, Esmaeil KK, et al. Comprehensive parametric analysis, sizing, and performance evaluation of a tubular direct contact membrane desalination system driven by heat pipe-based solar collectors. Energy Convers Manag 2022;274:116437. https://doi.org/10.1016/j.enconman.2022.116437.
[11] El-Agouz SA, Zayed ME, Abo Ghazala AM, Elbar ARA, Shahin M, Zakaria MY, et al. Solar thermal feed preheating techniques integrated with membrane distillation for seawater desalination applications: recent advances, retrofitting performance improvement strategies, and future perspectives. Process Saf Environ Protect 2022;164:595–612. https://doi.org/10.1016/j.psep.2022.06.044.
[12] Aboelmaaref MM, Zhao J, Li W, Ali ES, Askalany AA, Ghazy M, et al. Research on solar dish/Stirling engine driven adsorption-based desalination system for simultaneous co-generation of electricity and freshwater: numerical investigation. Case Stud Therm Eng 2023;47:103044. https://doi.org/10.1016/j.csite.2023.103044.
[13] Shoeibi S, Kargarsharifabad H, Rahbar N, Ahmadi G, Safaei MR. Performance evaluation of a solar still using hybrid nanofluid glass cooling-CFD simulation and environmental analysis. Sustain Energy Technol Assessments 2022;49:101728. https://doi.org/10.1016/j.seta.2021.101728.
[14] Ahmed MMZ, Alshammari F, Alatawi I, Alhadri M, Elashmawy M. A novel solar desalination system integrating inclined and tubular solar still with parabolic concentrator. Appl Therm Eng 2022;213:118665.
[15] Zhao Y, Ramadan O, Kong H, Xue X, Riffat S, Zheng H. Performance analysis and optimization of a novel high-efficiency flower-inspired solar still. Energy Convers Manag 2022;251:114878. https://doi.org/10.1016/j.enconman.2021.114878.
[16] Sharshir SW, Kandeal AW, Ellakany YM, Maher I, Khalil A, Swidan A, et al. Improving the performance of tubular solar still integrated with drilled carbonized wood and carbon black thin film evaporation. Sol Energy 2022;233:504–14. https://doi.org/10.1016/j.solener.2022.01.065.
[17] Maheswari KS, Mayandi K, Joe Patrick Gnanaraj S, Appadurai M. Effect of transparent glass cover material on double slope solar still productivity. Mater Today Proc 2022;62:5415–9. https://doi.org/10.1016/j.matpr.2022.03.702.
[18] Rafeek MTM, Muthu V, Athikesavan MM, Sathyamurthy R, Kabeel AE. Experimental investigation of an active inclined solar panel absorber solar still—energy and exergy analysis. Environ Sci Pollut Control Ser 2022;29:14005–18. https://doi.org/10.1007/s11356-021-16444-3.
[19] Alhadri M, Alatawi I, Alshammari F, Haleem MA, Heniegal AMA, Abdelaziz GB, et al. Design of a low-cost parabolic concentrator solar tracking system: tubular solar still application. J Sol Energy Eng 2022;144:1–10. https://doi.org/10.1115/1.4054232.
[20] Panchal HN, Patel S. An extensive review on different design and climatic parameters to increase distillate output of solar still. Renew Sustain Energy Rev 2017;69:750–8.
[21] Bloemer JW, Eibling JA, Irwin JR, Löf GOG. A practical basin-type solar still. Sol Energy 1965;9:197–200.
[22] Kudish AI, Evseev EG, Walter G, Priebe T. Simulation study on a solar desalination system utilizing an evaporator/condenser chamber. Energy Convers Manag 2003;44:1653–70.
[23] Kumar PV, Kumar A, Prakash O, Kaviti AK. Solar stills system design: a review. Renew Sustain Energy Rev 2015;51:153–81.
[24] Shoeibi S, Rahbar N, Esfahlani AA, Kargarsharifabad H. A comprehensive review of Enviro-Exergo-economic analysis of solar stills. Renew Sustain Energy Rev 2021;149:111404.
[25] Shoeibi S, Rahbar N, Esfahlani AA, Kargarsharifabad H. Improving the thermoelectric solar still performance by using nanofluids–Experimental study, thermodynamic modeling and energy matrices analysis. Sustain Energy Technol Assessments 2021;47:101339.
[26] Altarawneh I, Rawadieh S, Batiha M, Al-Makhadmeh L, Alrowwad S, Tarawneh M. Experimental and numerical performance analysis and optimization of single slope, double slope and pyramidal shaped solar stills. Desalination 2017;423:124–34. https://doi.org/10.1016/j.desal.2017.09.023.
[27] Rahbar N, Esfahani JA. Productivity estimation of a single-slope solar still: theoretical and numerical analysis. Energy 2013;49:289–97. https://doi.org/10.1016/j.energy.2012.10.023.
[28] Dunkle RV. Solar water distillation: the roof type still and a multiple effect diffusion still. In: Proc. International heat transfer conference. vol. 5. USA: University of Colorado; 1961. p. 895. 1961.

[29] Rahbar N, Esfahani JA. Productivity estimation of a single-slope solar still: theoretical and numerical analysis. Energy 2013;49:289–97. https://doi.org/10.1016/j.energy.2012.10.023.
[30] Sahota L, Tiwari GN. Effect of Al2O3 nanoparticles on the performance of passive double slope solar still. Sol Energy 2016;130:260–72. https://doi.org/10.1016/j.solener.2016.02.018.
[31] Selvaraj K, Natarajan A. Factors influencing the performance and productivity of solar stills-A review. Desalination 2018;435:181–7.
[32] Sharshir SW, Yang N, Peng G, Kabeel AE. Factors affecting solar stills productivity and improvement techniques: a detailed review. Appl Therm Eng 2016;100:267–84.
[33] Kabeel AE, Omara ZM, Younes MM. Techniques used to improve the performance of the stepped solar still—a review. Renew Sustain Energy Rev 2015;46:178–88.
[34] Lawag RA, Ali HM. Phase change materials for thermal management and energy storage: a review. J Energy Storage 2022;55:105602.
[35] Hassan F, Jamil F, Hussain A, Ali HM, Janjua MM, Khushnood S, et al. Recent advancements in latent heat phase change materials and their applications for thermal energy storage and buildings: a state of the art review. Sustain Energy Technol Assessments 2022;49:101646. https://doi.org/10.1016/j.seta.2021.101646.
[36] Thakur AK, Agarwal D, Khandelwal P, Dev S. Comparative study and yield productivity of nano-paint and nano-fluid used in a passive-type single basin solar still. In: Advances in smart grid and renewable energy: proceedings of ETAEERE-2016. Springer; 2018. p. 709–16.
[37] Sharshir SW, Joseph A, Kandeal AW, Hussien AA. Performance improvement of tubular solar still using nano-coated hanging wick thin film, ultrasonic atomizers, and cover cooling. Sustain Energy Technol Assessments 2022;52:102127.
[38] Kabeel AE, Sathyamurthy R, Sharshir SW, Muthumanokar A, Panchal H, Prakash N, et al. Effect of water depth on a novel absorber plate of pyramid solar still coated with TiO2 nano black paint. J Clean Prod 2019;213:185–91.
[39] Zanganeh P, Goharrizi AS, Ayatollahi S, Feilizadeh M. Nano-coated condensation surfaces enhanced the productivity of the single-slope solar still by changing the condensation mechanism. J Clean Prod 2020;265:121758.
[40] Thakur AK, Sathyamurthy R, Velraj R, Saidur R, Hwang J-Y. Augmented performance of solar desalination unit by utilization of nano-silicon coated glass cover for promoting drop-wise condensation. Desalination 2021;515:115191.
[41] Gangavathi P, Ramya G, Karuna MS, Jeyapiriya K, Magade PB, Manirathnam D. Influence of nanomaterial coated condensing surface on the productivity of evacuated tube assisted solar still. Mater Today Proc 2022;69:853–7.
[42] Thakur AK, Sathyamurthy R, Velraj R, Saidur R, Lynch I, Chaturvedi M, et al. Synergetic effect of absorber and condenser nano-coating on evaporation and thermal performance of solar distillation unit for clean water production. Sol Energy Mater Sol Cell 2022;240:111698.
[43] Ni G, Li G, Boriskina SV, Li H, Yang W, Zhang T, et al. Steam generation under one sun enabled by a floating structure with thermal concentration. Nat Energy 2016;1:16126.
[44] Fu Y, Wang G, Ming X, Liu X, Hou B, Mei T, et al. Oxygen plasma treated graphene aerogel as a solar absorber for rapid and efficient solar steam generation. Carbon N Y 2018;130:250–6.
[45] Liu Z, Song H, Ji D, Li C, Cheney A, Liu Y, et al. Extremely cost-effective and efficient solar vapor generation under nonconcentrated illumination using thermally isolated black paper. Global Challenges 2017;1:1600003.
[46] Liu H, Chen C, Chen G, Kuang Y, Zhao X, Song J, et al. High-performance solar steam device with layered channels: artificial tree with a reversed design. Adv Energy Mater 2018;8:1701616.
[47] Jiang F, Li T, Li Y, Zhang Y, Gong A, Dai J, et al. Wood-based nanotechnologies toward sustainability. Adv Mater 2018;30:1703453.
[48] Jin Y, Chang J, Shi Y, Shi L, Hong S, Wang P. A highly flexible and washable nonwoven photothermal cloth for efficient and practical solar steam generation. J Mater Chem A Mater 2018;6:7942–9.
[49] Elimelech M, Phillip WA. The future of seawater desalination: energy, technology, and the environment. Science 2011;333:712–7. 1979.
[50] Pendergast MM, Hoek EMV. A review of water treatment membrane nanotechnologies. Energy Environ Sci 2011;4:1946–71.
[51] Zhang P, Liao Q, Yao H, Huang Y, Cheng H, Qu L. Direct solar steam generation system for clean water production. Energy Storage Mater 2019;18:429–46.
[52] Nazari S, Safarzadeh H, Bahiraei M. Performance improvement of a single slope solar still by employing thermoelectric cooling channel and copper oxide nanofluid: an experimental study. J Clean Prod 2019;208:1041–52.
[53] Sharshir SW, Peng G, Wu L, Yang N, Essa FA, Elsheikh AH, et al. Enhancing the solar still performance using nanofluids and glass cover cooling: experimental study. Appl Therm Eng 2017;113:684–93.
[54] Shoeibi S, Rahbar N, Esfahlani AA, Kargarsharifabad H. Improving the thermoelectric solar still performance by using nanofluids–Experimental study, thermodynamic modeling and energy matrices analysis. Sustain Energy Technol Assessments 2021;47:101339.
[55] Elmaadawy K, Kandeal AW, Khalil A, Elkadeem MR, Liu B, Sharshir SW. Performance improvement of double slope solar still via combinations of low cost materials integrated with glass cooling. Desalination 2021;500:114856.
[56] Nazari S, Safarzadeh H, Bahiraei M. Experimental and analytical investigations of productivity, energy and exergy efficiency of a single slope solar still enhanced with thermoelectric channel and nanofluid. Renew Energy 2019;135:729–44.
[57] Parsa SM, Rahbar A, Koleini MH, Aberoumand S, Afrand M, Amidpour M. A renewable energy-driven thermoelectric-utilized solar still with external condenser loaded by silver/nanofluid for simultaneously water disinfection and desalination. Desalination 2020;480:114354.
[58] Khairat Dawood MM, Shehata AI, elnaby Kabeel A, Elharidi AM, Abdelsalam Taha A, Bayoumi S, et al. Increasing the freshwater productivity of a solar still loaded with CuO nanofluids using vibration motion and cover cooling techniques. Int J Energy Res 2021;45:9099–115.
[59] Shoeibi S, Ali Agha Mirjalily S, Kargarsharifabad H, Panchal H, Dhivagar R. Comparative study of double-slope solar still, hemispherical solar still, and tubular solar still using Al2O3/water film cooling: a numerical study and CO2 mitigation analysis. Environ Sci Pollut Control Ser 2022;29:65353–69.
[60] Chamkha AJ, Rufuss DDW, Kabeel AE, Sathyamurthy R, Abdelgaid M, Manokar AM, et al. Augmenting the potable water produced from single slope solar still using CNT-doped paraffin wax as energy storage: an experimental approach. J Braz Soc Mech Sci Eng 2020;42:625. https://doi.org/10.1007/s40430-020-02703-w.
[61] Rajasekhar G, Eswaramoorthy M. Performance evaluation on solar still integrated with nano-composite phase change materials. Appl Sol Energy 2015;51:15–21.
[62] Kabeel AE, Sathyamurthy R, Manokar AM, Sharshir SW, Essa FA, Elshiekh AH. Experimental study on tubular solar still using Graphene Oxide Nano particles in Phase Change Material (NPCM's) for fresh water production. J Energy Storage 2020;28:101204. https://doi.org/10.1016/j.est.2020.101204.
[63] Sajjad U, Hussain I, Hamid K, Bhat SA, Ali HM, Wang C-C. A deep learning method for estimating the boiling heat transfer coefficient of porous surfaces. J Therm Anal Calorim 2021;145:1911–23.
[64] Manoj Kumar P, Sudarvizhi D, Prakash KB, Anupradeepa AM, Boomiha Raj S, Shanmathi S, et al. Investigating a single slope solar still with a nano-phase change material. Mater Today Proc 2021. https://doi.org/10.1016/j.matpr.2020.12.804.
[65] Rufuss DDW, Iniyan S, Suganthi L, Davies PA. Nanoparticles enhanced phase change material (NPCM) as heat storage in solar still application for productivity enhancement. Energy Proc 2017;141:45–9.
[66] Behura A, Gupta HK. Use of nanoparticle-embedded phase change material in solar still for productivity enhancement. Mater Today Proc 2021;45:3904–7.
[67] Abdullah AS, Omara ZM, Essa FA, Alqsair UF, Aljaghtham M, Mansir IB, et al. Enhancing trays solar still performance using wick finned absorber, nano-enhanced PCM. Alex Eng J 2022;61:12417–30.
[68] Sonker VK, Chakraborty JP, Sarkar A. Development of a frugal solar still using phase change material and nanoparticles integrated with commercialization through a novel economic model. J Energy Storage 2022;51:104569.
[69] Selimefendigil F, Şirin C, Öztop HF. Experimental analysis of combined utilization of CuO nanoparticles in latent heat storage unit and absorber coating in a single-slope solar desalination system. Sol Energy 2022;233:278–86.
[70] Abdelaziz GB, Algazzar AM, El-Said EMS, Elsaid AM, Sharshir SW, Kabeel AE, et al. Performance enhancement of tubular solar still using nano-enhanced energy storage material integrated with v-corrugated aluminum basin, wick, and nanofluid. J Energy Storage 2021;41:102933.
[71] Kandeal AW, El-Shafai NM, Abdo MR, Thakur AK, El-Mehasseb IM, Maher I, et al. Improved thermo-economic performance of solar desalination via copper chips, nanofluid, and nano-based phase change material. Sol Energy 2021;224:1313–25.
[72] Abdullah AS, Omara ZM, Bacha H Ben, Younes MM. Employing convex shape absorber for enhancing the performance of solar still desalination system. J Energy Storage 2022;47:103573.
[73] Yousef MS, Hassan H. An experimental work on the performance of single slope solar still incorporated with latent heat storage system in hot climate conditions. J Clean Prod 2019;209:1396–410.
[74] Amarloo A, Shafii MB. Enhanced solar still condensation by using a radiative cooling system and phase change material. Desalination 2019;467:43–50.
[75] Mousa H, Naser J. Experimental measurement and theoretical prediction of the temperatures and the productivity of a continuous solar desalination unit with PCM. Appl Sol Energy 2021;57:170–80.
[76] Mazraeh AE, Babayan M, Yari M, Sefidan AM, Saha SC. Theoretical study on the performance of a solar still system integrated with PCM-PV module for sustainable water and power generation. Desalination 2018;443:184–97. https://doi.org/10.1016/j.desal.2018.05.024.
[77] Yousef MS, Hassan H, Kodama S, Sekiguchi H. An experimental study on the performance of single slope solar still integrated with a PCM-based pin-finned heat sink. Energy Proc 2019;156:100–4. https://doi.org/10.1016/j.egypro.2018.11.102.
[78] Anand A, Kant K, Shukla A, Sharma A. Latent heat storage for solar still applications. Solar Desalination Technol 2019:293–323.
[79] Naim MM, Abd El Kawi MA. Non-conventional solar stills Part 1. Non-conventional solar stills with charcoal particles as absorber medium. Desalination 2003;153:55–64.
[80] Kabeel AE, Abdelgaied M, Eisa A. Enhancing the performance of single basin solar still using high thermal conductivity sensible storage materials. J Clean Prod 2018;183:20–5.
[81] Yousef MS, Hassan H. Energetic and exergetic performance assessment of the inclusion of phase change materials (PCM) in a solar distillation system. Energy Convers Manag 2019;179:349–61.
[82] Sathish Kumar TR, Jegadheeswaran S, Chandramohan P. Performance investigation on fin type solar still with paraffin wax as energy storage media. J Therm Anal Calorim 2019;136:101–12.
[83] Kabeel AE, Abdelaziz GB, El-Said EMS. Experimental investigation of a solar still with composite material heat storage: energy, exergy and economic analysis. J Clean Prod 2019;231:21–34.
[84] Ho ZY, Bahar R, Koo CH. Passive solar stills coupled with Fresnel lens and phase change material for sustainable solar desalination in the tropics. J Clean Prod 2022;334:130279.

[85] Mousa H, Naser J, Gujarathi AM, Al-Sawafi S. Experimental study and analysis of solar still desalination using phase change materials. J Energy Storage 2019;26:100959. https://doi.org/10.1016/j.est.2019.100959.
[86] Sarhaddi F, Farshchi Tabrizi F, Aghaei Zoori H, Mousavi SAHS. Comparative study of two weir type cascade solar stills with and without PCM storage using energy and exergy analysis. Energy Convers Manag 2017;133:97–109. https://doi.org/10.1016/j.enconman.2016.11.044.
[87] El Hadi Attia M, Zayed ME, Kabeel AE, Abdullah AS, Abdelgaied M. Energy, exergy, and economic analyses of a modified hemispherical solar distiller augmented with convex absorber basin, wicks, and PCM. Sol Energy 2023;261:43–54. https://doi.org/10.1016/j.solener.2023.05.057.
[88] Rashid FL, Shareef AS, Alwan HF. Enhancement of fresh water production in solar still using new phase change materials. J Adv Res Fluid Mech Thermal Sci n.d.;61:63–72..
[89] Sampathkumar A, Natarajan SK. Experimental analysis on single slope solar still by the inclusion of agar-agar (Eucheuma) fibre and micro phase change material for the productivity enhancement. J Energy Storage 2022;50:104284.
[90] Abdelgaied M, Attia MEH, Kabeel AE, Zayed ME. Improving the thermo-economic performance of hemispherical solar distiller using copper oxide nanofluids and phase change materials: experimental and theoretical investigation. Sol Energy Mater Sol Cell 2022;238:111596. https://doi.org/10.1016/j.solmat.2022.111596.
[91] Hammad FA, Shalaby SM, Kabeel AE, Zayed ME. Experimental investigation and thermo-economic performance analysis of a modified solar distiller design with thermal storage material and v-corrugated absorber basin. J Energy Storage 2022;52:105020. https://doi.org/10.1016/j.est.2022.105020.
[92] Kabeel AE, Attia MEH, Zayed ME, Abdelgaied M, Abdullah AS, El-Maghlany WM. Performance enhancement of a v-corrugated basin hemispherical solar distiller combined with reversed solar collector: an experimental approach. Renew Energy 2022;190:330–7. https://doi.org/10.1016/j.renene.2022.03.107.
[93] Kateshia J, Lakhera V. A comparative study of various fatty acids as phase change material to enhance the freshwater productivity of solar still. J Energy Storage 2022;48:103947.
[94] Ravishankara S, Nagarajan PK, Vijayakumar D, Jawahar MK. Phase change material on augmentation of fresh water production using pyramid solar still. Int J Renew Energy Dev 2013;2:1–15.
[95] Dashtban M, Tabrizi FF. Thermal analysis of a weir-type cascade solar still integrated with PCM storage. Desalination 2011;279:415–22.
[96] Kabeel AE, Teamah MA, Abdelgaied M, Aziz GBA. Modified pyramid solar still with v-corrugated absorber plate and PCM as a thermal storage medium. J Clean Prod 2017;161:881–7.
[97] Benhammou M, Sahli Y. Energetic and exergetic analysis of a sloped solar still integrated with a separated heat storage system incorporating phase change material. J Energy Storage 2021;40:102705.
[98] Alshammari F, Elashmawy M, Ahmed MMZ. Cleaner production of freshwater using multi-effect tubular solar still. J Clean Prod 2021;281:125301.
[99] Sathyamurthy R, Nagarajan PK, Subramani J, Vijayakumar D, Ali KMA. Effect of water mass on triangular pyramid solar still using phase change material as storage medium. Energy Proc 2014;61:2224–8.
[100] Abdelgaied M, Zakaria Y, Kabeel AE, Essa FA. Improving the tubular solar still performance using square and circular hollow fins with phase change materials. J Energy Storage 2021;38:102564.
[101] Kannan BT, Madhu B, Kabeel AE, Thakur AK, Velraj R, Lynch I, et al. Improved freshwater generation via hemispherical solar desalination unit using paraffin wax as phase change material encapsulated in waste aluminium cans. Desalination 2022;538:115907.
[102] Ajdari H, Ameri A. Performance assessment of an inclined stepped solar still integrated with PCM and CuO/GO nanocomposite as a nanofluid. J Build Eng 2022;49:104090.
[103] Subramanian RS, Kumaresan G, Ajith R, Sabarivasan U, Gowthamaan KK, Anudeep S. Performance analysis of modified solar still integrated with flat plate collector. Mater Today Proc 2021;45:1382–7.
[104] Chaichan MT, Kazem HA. Single slope solar distillator productivity improvement using phase change material and Al2O3 nanoparticle. Sol Energy 2018;164:370–81.
[105] Rufuss DDW, Suganthi L, Iniyan S, Davies PA. Effects of nanoparticle-enhanced phase change material (NPCM) on solar still productivity. J Clean Prod 2018;192:9–29.
[106] Yousef MS, Hassan H. Assessment of different passive solar stills via exergoeconomic, exergoenvironmental, and exergoenviroeconomic approaches: a comparative study. Sol Energy 2019;182:316–31.
[107] Kabeel AE, El-Maghlany WM, Abdelgaied M, Abdel-Aziz MM. Performance enhancement of pyramid-shaped solar stills using hollow circular fins and phase change materials. J Energy Storage 2020;31:101610. https://doi.org/10.1016/j.est.2020.101610.
[108] Cheng W-L, Huo Y-K, Nian Y-L. Performance of solar still using shape-stabilized PCM: experimental and theoretical investigation. Desalination 2019;455:89–99. https://doi.org/10.1016/j.desal.2019.01.007.
[109] Tuly SS, Hassan R, Das BK, Sarker MRI. Investigating the energetic, exergetic, and sustainability aspects of a solar still integrating fins, wick, phase change materials, and external condenser. J Energy Storage 2022;55:105462.
[110] Suraparaju SK, Natarajan SK. Productivity enhancement of single-slope solar still with novel bottom finned absorber basin inserted in phase change material (PCM): techno-economic and enviro-economic analysis. Environ Sci Pollut Control Ser 2021;28:45985–6006.
[111] Ahmed H, Najib A, Zaidi AA, Naseer MN, Kim B. Modeling, design optimization and field testing of a solar still with corrugated absorber plate and phase change material for Karachi weather conditions. Energy Rep 2022;8:11530–46.
[112] Nwosu EC, Nwaji GN, Ononogbo C, Ofong I, Nwadinobi PC, Ogueke NV, et al. Numerical and experimental study of a single-slope double-effect solar still integrated with paraffin wax. Energy Nexus 2022:100155.
[113] Hansen RS, Mary MBQ, Subramanian SS, Raj JA, Gnanaraj SJP, Appadurai M. Utilization of PCM in inclined and single basin solar stills to improve the daily productivity. Mater Today Proc 2022;62:967–72.
[114] Mevada D, Panchal H, Ahmadein M, Zayed ME, Alsaleh NA, Djuansjah J, et al. Investigation and performance analysis of solar still with energy storage materials: an energy-exergy efficiency analysis. Case Stud Therm Eng 2022;29:101687.
[115] Sathish Kumar TR, Jegadheeswaran S. Experimental investigation on finned solar still with enhanced thermal energy storage. J Therm Sci Eng Appl 2022;14:91001.
[116] Jahanpanah M, Sadatinejad SJ, Kasaeian A, Jahangir MH, Sarrafha H. Experimental investigation of the effects of low-temperature phase change material on single-slope solar still. Desalination 2021;499:114799. https://doi.org/10.1016/j.desal.2020.114799.
[117] Thakur AK, Sathyamurthy R, Velraj R. Development of candle soot dispersed phase change material for improving water generation potential of tubular solar distillation unit. Sol Energy Mater Sol Cell 2022;241:111748.
[118] Asbik M, Boushaba H, Hafs H, Koukouch A, Sabri A, Manokar AM. Investigating the effect of sensible and latent heat storage materials on the performance of a single basin solar still during winter days. J Energy Storage 2021;44:103480.
[119] Kumar D, Layek A, Kumar A. Performance enhancement of single slope solar still integrated with flat plate collector for different basin water depth. In: AIP conf proc, vol. 2273. AIP Publishing LLC; 2020, 50007.
[120] Abu-Arabi M, Al-harahsheh M, Ahmad M, Mousa H. Theoretical modeling of a glass-cooled solar still incorporating PCM and coupled to flat plate solar collector. J Energy Storage 2020;29:101372. https://doi.org/10.1016/j.est.2020.101372.
[121] Al-Harahsheh M, Abu-Arabi M, Ahmad M, Mousa H. Self-powered solar desalination using solar still enhanced by external solar collector and phase change material. Appl Therm Eng 2022;206:118118.
[122] Toosi SSA, Goshayeshi HR, Heris SZ. Experimental investigation of stepped solar still with phase change material and external condenser. J Energy Storage 2021;40:102681.
[123] Tuly SS, Rahman MS, Sarker MRI, Beg RA. Combined influence of fin, phase change material, wick, and external condenser on the thermal performance of a double slope solar still. J Clean Prod 2021;287:125458. https://doi.org/10.1016/j.jclepro.2020.125458.
[124] Essa FA, Abdullah AS, Alawee WH, Alarjani A, Alqsair UF, Shanmugan S, et al. Experimental enhancement of tubular solar still performance using rotating cylinder, nanoparticles' coating, parabolic solar concentrator, and phase change material. Case Stud Therm Eng 2022;29:101705.
[125] Hafs H, Asbik M, Boushaba H, Koukouch A, Zaaoumi A, Bah A, et al. Numerical simulation of the performance of passive and active solar still with corrugated absorber surface as heat storage medium for sustainable solar desalination technology. Groundw Sustain Dev 2021;14:100610.
[126] Sathish D, Jegadheeswaran S, Veeramanikandan M. Enhancing the thermo-economic performance of mobile solar desalination system with dual reflectors, phase change materials and insulator cover: experimental investigations. Appl Therm Eng 2022;217:119210.
[127] Elashmawy M, Alhadri M, Ahmed MMZ. Enhancing tubular solar still performance using novel PCM-tubes. Desalination 2021;500:114880. https://doi.org/10.1016/j.desal.2020.114880.
[128] Maridurai T, Rajkumar S, Arunkumar M, Mohanavel V, Arul K, Madhesh D, et al. Performance study on phase change material integrated solar still coupled with solar collector. Mater Today Proc 2022;59:1319–23.
[129] Al-harahsheh M, Abu-Arabi M, Mousa H, Alzghoul Z. Solar desalination using solar still enhanced by external solar collector and PCM. Appl Therm Eng 2018;128:1030–40. https://doi.org/10.1016/j.applthermaleng.2017.09.073.
[130] Kabeel AE, Harby K, Abdelgaied M, Eisa A. Augmentation of a developed tubular solar still productivity using hybrid storage medium and CPC: an experimental approach. J Energy Storage 2020;28:101203. https://doi.org/10.1016/j.est.2020.101203.
[131] Kabeel AE, Khairat Dawood MM, Nabil T, Alonafal BE. Improving the performance of stepped solar still using a graphite and PCM as hybrid store materials with internal reflectors coupled with evacuated tube solar collector. Heat Mass Tran 2020;56:891–9.
[132] Abd Elbar AR, Hassan H. Enhancement of hybrid solar desalination system composed of solar panel and solar still by using porous material and saline water preheating. Sol Energy 2020;204:382–94.
[133] Nian Y-L, Huo Y-K, Cheng W-L. Study on annual performance of the solar still using shape-stabilized phase change materials with economic analysis. Sol Energy Mater Sol Cell 2021;230:111263.
[134] Tuly SS, Ayon ABS, Hassan R, Das BK, Khan RH, Sarker MRI. Performance investigation of active double slope solar stills incorporating internal sidewall reflector, hollow circular fins, and nanoparticle-mixed phase change material. J Energy Storage 2022;55:105660.
[135] Poonia S, Singh AK, Jain D. Performance evaluation of PCM based solar concentrator type desalination device. Mater Today Proc 2022;62:5194–200.
[136] Ghorbani B, Mehrpooya M. Thermo-economic analysis of a solar-driven multi-stage desalination unit equipped with a phase change material storage system to provide heating and fresh water for a residential complex. J Energy Storage 2020;30:101555.

[137] Dhivagar R, Deepanraj B, Mohanraj M, Prakash A. Thermal performance, cost effectiveness and environmental analysis of a heat pump assisted regenerative solar still using slack wax as heat storage material. Sustain Energy Technol Assessments 2022;52:102090.
[138] Shehata AI, Kabeel AE, Dawood MMK, Elharidi AM, Abd_Elsalam A, Ramzy K, et al. Enhancement of the productivity for single solar still with ultrasonic humidifier combined with evacuated solar collector: an experimental study. Energy Convers Manag 2020;208:112592.
[139] Mohanraj M, Karthick L, Dhivagar R. Performance and economic analysis of a heat pump water heater assisted regenerative solar still using latent heat storage. Appl Therm Eng 2021;196:117263.
[140] Dawood MMK, Nabil T, Kabeel AE, Shehata AI, Abdalla AM, Elnaghi BE. Experimental study of productivity progress for a solar still integrated with parabolic trough collectors with a phase change material in the receiver evacuated tubes and in the still. J Energy Storage 2020;32:102007.
[141] Hedayati-Mehdiabadi E, Sarhaddi F, Sobhnamayan F. Exergy performance evaluation of a basin-type double-slope solar still equipped with phase-change material and PV/T collector. Renew Energy 2020;145:2409–25.
[142] Shoeibi S, Kargarsharifabad H, Rahbar N. Effects of nano-enhanced phase change material and nano-coated on the performance of solar stills. J Energy Storage 2021;42:103061.
[143] Shoeibi S, Kargarsharifabad H, Mirjalily SAA, Muhammad T. Solar district heating with solar desalination using energy storage material for domestic hot water and drinking water–environmental and economic analysis. Sustain Energy Technol Assessments 2022;49:101713.
[144] Abdullah AS, Omara ZM, Essa FA, Younes MM, Shanmugan S, Abdelgaied M, et al. Improving the performance of trays solar still using wick corrugated absorber, nano-enhanced phase change material and photovoltaics-powered heaters. J Energy Storage 2021;40:102782.
[145] Shoeibi S, Mirjalily SAA, Kargarsharifabad H, Khiadani M, Panchal H. A comprehensive review on performance improvement of solar desalination with applications of heat pipes. Desalination 2022;540:115983.
[146] Rastegar S, Kargarsharifabad H, Rahbar N, Shafii MB. Distilled water production with combination of solar still and thermosyphon heat pipe heat exchanger coupled with indirect water bath heater–experimental study and thermoeconomic analysis. Appl Therm Eng 2020;176:115437.
[147] Faegh M, Shafii MB. Experimental investigation of a solar still equipped with an external heat storage system using phase change materials and heat pipes. Desalination 2017;409:128–35.
[148] Behnam P, Shafii MB. Examination of a solar desalination system equipped with an air bubble column humidifier, evacuated tube collectors and thermosyphon heat pipes. Desalination 2016;397:30–7.
[149] Patel M, Patel C, Panchal H. Performance analysis of conventional triple basin solar still with evacuated heat pipes, corrugated sheets and storage materials. Groundw Sustain Dev 2020;11:100387.
[150] Khalilmoghadam P, Rajabi-Ghahnavieh A, Shafii MB. A novel energy storage system for latent heat recovery in solar still using phase change material and pulsating heat pipe. Renew Energy 2021;163:2115–27.
[151] Mamouri SJ, Derami HG, Ghiasi M, Shafii MB, Shiee Z. Experimental investigation of the effect of using thermosyphon heat pipes and vacuum glass on the performance of solar still. Energy 2014;75:501–7.
[152] Fallahzadeh R, Aref L, Gholamiarjenaki N, Nonejad Z, Saghi M. Experimental investigation of the effect of using water and ethanol as working fluid on the performance of pyramid-shaped solar still integrated with heat pipe solar collector. Sol Energy 2020;207:10–21.
[153] Shoeibi S, Kargarsharifabad H, Rahbar N, Khosravi G, Sharifpur M. An integrated solar desalination with evacuated tube heat pipe solar collector and new wind ventilator external condenser. Sustain Energy Technol Assessments 2022;50:101857.
[154] Kabeel AE, Hamed AM, El-Agouz SA. Cost analysis of different solar still configurations. Energy 2010;35:2901–8.
[155] Fath HES, El-Samanoudy M, Fahmy K, Hassabou A. Thermal-economic analysis and comparison between pyramid-shaped and single-slope solar still configurations. Desalination 2003;159:69–79.
[156] Kabeel AE, El-Samadony YAF, El-Maghlany WM. Comparative study on the solar still performance utilizing different PCM. Desalination 2018;432:89–96.
[157] Kateshia J, Lakhera VJ. Analysis of solar still integrated with phase change material and pin fins as absorbing material. J Energy Storage 2021;35:102292. https://doi.org/10.1016/j.est.2021.102292.
[158] Yousef MS, Hassan H, Sekiguchi H. Energy, exergy, economic and enviroeconomic (4E) analyses of solar distillation system using different absorbing materials. Appl Therm Eng 2019;150:30–41.
[159] Velmurugan V, Gopalakrishnan M, Raghu R, Srithar K. Single basin solar still with fin for enhancing productivity. Energy Convers Manag 2008;49:2602–8.
[160] Kabeel AE, Abdelgaied M. Improving the performance of solar still by using PCM as a thermal storage medium under Egyptian conditions. Desalination 2016;383:22–8.
[161] Dwivedi VK, Tiwari GN. Thermal modeling and carbon credit earned of a double slope passive solar still. Desalination Water Treat 2010;13:400–10.
[162] Joshi P, Tiwari GN. Energy matrices, exergo-economic and enviro-economic analysis of an active single slope solar still integrated with a heat exchanger: a comparative study. Desalination 2018;443:85–98.
[163] Parsa SM, Rahbar A, Javadi D, Koleini MH, Afrand M, Amidpour M. Energy-matrices, exergy, economic, environmental, exergoeconomic, enviroeconomic, and heat transfer (6E/HT) analysis of two passive/active solar still water desalination nearly 4000m: altitude concept. J Clean Prod 2020;261:121243.
[164] Abd Elbar AR, Yousef MS, Hassan H. Energy, exergy, exergoeconomic and enviroeconomic (4E) evaluation of a new integration of solar still with photovoltaic panel. J Clean Prod 2019;233:665–80.
[165] Parsa SM, Yazdani A, Javadi D, Afrand M, Karimi N, Ali HM. Selecting efficient side of thermoelectric in pyramid-shape solar desalination units incorporated phase change material (PCM), nanoparticle, turbulator with battery storage powered by photovoltaic. J Energy Storage 2022;51:104448. https://doi.org/10.1016/j.est.2022.104448.
[166] Saeed AA, Alharthi AM, Aldosari KM, Abdullah AS, Essa FA, Alqsair UF, et al. Improving the drum solar still performance using corrugated drum and nano-based phase change material. J Energy Storage 2022;55:105647.
[167] Tuly SS, Islam MS, Hassan R, Das BK, Sarker MRI. Investigation of a modified double slope solar still integrated with nanoparticle-mixed phase change materials: energy, exergy, exergo-economic, environmental, and sustainability analyses. Case Stud Therm Eng 2022;37:102256.
[168] Singh DB, Tiwari GN. Effect of energy matrices on life cycle cost analysis of partially covered photovoltaic compound parabolic concentrator collector active solar distillation system. Desalination 2016;397:75–91.
[169] Singh DB, Tiwari GN, Al-Helal IM, Dwivedi VK, Yadav JK. Effect of energy matrices on life cycle cost analysis of passive solar stills. Sol Energy 2016;134:9–22.
[170] Singh DB, Tiwari GN. Performance analysis of basin type solar stills integrated with N identical photovoltaic thermal (PVT) compound parabolic concentrator (CPC) collectors: a comparative study. Sol Energy 2017;142:144–58.
[171] Singh DB, Tiwari GN. Enhancement in energy metrics of double slope solar still by incorporating N identical PVT collectors. Sol Energy 2017;143:142–61.
[172] Singh DB, Al-Helal IM. Energy metrics analysis of N identical evacuated tubular collectors integrated double slope solar still. Desalination 2018;432:10–22.
[173] Sharma SK, Singh DB, Mallick A, Gupta SK. Energy metrics and efficiency analyses of double slope solar distiller unit augmented with N identical parabolic concentrator integrated evacuated tubular collectors: a comparative study. Desalination Water Treat 2020;195:40–56.
[174] Singh DB, Tiwari GN. Exergoeconomic, enviroeconomic and productivity analyses of basin type solar stills by incorporating N identical PVT compound parabolic concentrator collectors: a comparative study. Energy Convers Manag 2017;135:129–47.
[175] Singh DB, Kumar N, Kumar S, Dwivedi VK, Yadav JK, Tiwari GN. Enhancement in exergoeconomic and enviroeconomic parameters for single slope solar still by incorporating N identical partially covered photovoltaic collectors. J Sol Energy Eng 2018;140.
[176] Yousef MS, Hassan H. Energy payback time, exergoeconomic and enviroeconomic analyses of using thermal energy storage system with a solar desalination system: an experimental study. J Clean Prod 2020;270:122082.
[177] Pal P, Dev R, Singh D, Ahsan A. Energy matrices, exergoeconomic and enviroeconomic analysis of modified multi–wick basin type double slope solar still. Desalination 2018;447:55–73.
[178] Sahota L, Tiwari GN. Energy matrices, enviroeconomic and exergoeconomic analysis of passive double slope solar still with water based nanofluids. Desalination 2017;409:66–79.
[179] Sahota L, Tiwari GN. Exergoeconomic and enviroeconomic analyses of hybrid double slope solar still loaded with nanofluids. Energy Convers Manag 2017;148:413–30.
[180] Shoeibi S, Ali Agha Mirjalily S, Kargarsharifabad H, Panchal H, Dhivagar R. Comparative study of double-slope solar still, hemispherical solar still, and tubular solar still using Al2O3/water film cooling: a numerical study and CO2 mitigation analysis. Environ Sci Pollut Control Ser 2022;29:65353–69.
[181] Agrawal R, Singh KDP. Experimental investigation and computational modelling of double slope solar still integrated with eutectic phase change material. J Energy Storage 2022;52:104802.
[182] Sonawane C, Alrubaie AJ, Panchal H, Chamkha AJ, Jaber MM, Oza AD, et al. Investigation on the impact of different absorber materials in solar still using CFD simulation—economic and environmental analysis. Water (Basel) 2022;14:3031.
[183] Modi KV, Patel UN, Patel SJ, Patel JN, Patel SR. Efficacy of partially and fully submerged circular cross-section metal hollow-fins and black cotton cloth wick-segments on a single-basin dual-slope solar still. J Clean Prod 2022;344:131059.
[184] Sharshir SS, Abd Elaziz M, Elsheikh A. Augmentation and prediction of wick solar still productivity using artificial neural network integrated with tree–seed algorithm. Int J Environ Sci Technol 2022:1–16.
[185] Negi P, Dobriyal R, Singh DB, Badhotiya GK. Materials Today: proceedings A review on passive and active solar still using phase change materials. Mater Today Proc 2021;46:10433–8.
[186] Chhabra S, Verma AS, Gupta A, Kumar R, Karnwal A, Kumar A, et al. Attempts to raise the solar still outcome: a short review. Mater Today Proc 2022;64:1375–9.
[187] Purnachandrakumar D, Mittal G, Sharma RK, Singh DB, Tiwari S, Sinhmar H. Review on performance assessment of solar stills using computational fluid dynamics (CFD). Environ Sci Pollut Control Ser 2022;29:38673–714.
[188] Singh DB, Bansal G, Yadav JK, Kumar N, Tiwari S, Raturi A. Exergoeconomic and enviroeconomic analyses of single slope solar desalination unit loaded with/without nanofluid: a comprehensive review. In: IOP conf ser mater sci eng, vol. 748. IOP Publishing; 2020, 12031.
[189] Patel RV, Bharti K, Singh G, Kumar R, Chhabra S, Singh DB. Solar still performance investigation by incorporating the shape of basin liner: a short review. Mater Today Proc 2021;43:597–604.
[190] Singh G, Singh DB, Kumar S, Bharti K, Chhabra S. A review of inclusion of nanofluids on the attainment of different types of solar collectors. Mater Today Proc 2021;38:153–9.

[191] Singh DB, Bansal G, Yadav JK, Kumar N, Singh M. Exergoeconomic and enviroeconomic analyses of double slope solar desalination unit loaded with/without nanofluid: a comparative study. In: Proceedings of international conference in mechanical and energy technology: ICMET 2019. India: Springer; 2020. p. 807–15.

[192] Singh AK, Singh DB, Dwivedi VK, Tiwari GN, Gupta A. Water purification using solar still with/without nano-fluid: a review. Mater Today Proc 2020;21:1700–6.

[193] Dharamveer Samsher, Singh DB, Singh AK, Kumar N. Solar distiller unit loaded with nanofluid—a short review. Adv Interdiscipl Eng: Select Proc FLAME 2018 2019:241–7.

[194] Singh AK, Singh DB, Dwivedi VK, Kumar N, Yadav JK. A review of performance enhancement in solar desalination systems with the application of nanofluids. In: 2018 international conference on advances in computing, communication control and networking (ICACCCN). IEEE; 2018. p. 814–9.

[195] Haridwar P, Pratap K, Yadav RK, Ashis M, Navneet K, Singh DB. Sensitivity analysis of N identical partially covered (50%) PVT compound parabolic concentrator collectors integrated double slope solar distiller unit. Desalination Water Treat 2019;153:54–64.

[196] Bharti K, Manwal S, Kishore C, Yadav RK, Tiwar P, Singh DB. Sensitivity analysis of N alike partly covered PVT flat plate collectors integrated double slope solar distiller unit. Desalination Water Treat 2021;211:45–59.

[197] Raturia A, Dobriyala R, Sharmab RK, Dwivedic A, Singhd SP, Singha DB. Sensitivity investigation for solar still of double slope type included with N similar CPC integrated ETC by incorporating yield and efficiency. Desalination Water Treat 2021;244:12–26.

[198] Singh AR, Agarwal AB, Singh DB. Sensitivity analysis of double slope solar still having compound parabolic concentrator integrated ETCs by incorporating heat transfer coefficients, exergy gain and exergy efficiency. Desalination Water Treat 2022;276:13–27.

[199] Chen WL, Xie G. Performance of multi-stage tubular solar still operating under vacuum. Renew Energy 2022;201:34–46.

[200] Raturi A, Singh DB, Patil PP, Sharma AK. Sensitivity analysis of a solar still of a single slope type included with N similar evacuated tubular collectors having series connection. Desalin Water Treat 2021;234:309–23.