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Enhancing solar still productivity with organic phase change materials: A literature review

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ABSTRACT

Solar still systems often include organic phase change materials (PCMs) because of their remarkable thermophysical characteristics. Numerous innovative PCMs have been developed and subsequently incorporated into solar still applications, resulting in improved distillate yields in these systems. This enhancement has been extensively analyzed and discussed. An enhancement of 143.78% in distillate yield was reported for the active solar still that utilized lauric acid. On the other hand, the passive solar still saw an increase in distillate production of 124.74% when using soy wax and 109.3% when using beeswax. The selection of PCM necessitates meticulous evaluation, considering aspects like cost, compatibility with the container, and its environmental implications, all of which have been comprehensively examined. The analysis centers on solar distillation systems, exploring a range of modifications and their incorporation with various PCMs. In light of the findings, it is prudent to consider modifications to the solar still and the meticulous selection of appropriate PCM for future studies.

1. Introduction

As the global community endeavours to mitigate greenhouse gas emissions, it is imperative to create state-of-the-art technology to transform renewable energy sources into usable energy [1]. Achieving this requires thoroughly understanding renewable energy sources and advocating for their broad adoption. This enables a perpetual upgrade of the existing technology that could lead to a sustainable environment and progress in the world [2]. Every upgrade in technology directly or indirectly relates to some form of energy; one of the most important is heat [3]. Storage and transfer of heat for any system or subsystem is crucial; for an efficient execution of any system, the role of heat storage and heat transfer is of utmost importance [4]. One such heat transfer application can be seen in solar stills, which began in the late 18th century to purify impure water. Since then, it has been viewed as an alternative to the existing water purifying system, which consumes energy input as solar radiation. The significant advantage of solar still over existing water purifying systems is its ability to harness the sun's limitless power. However, the rate at which solar still delivers freshwater yield is debatable and hence not preferred in many practical applications [5]. Several methods have been adopted to improve the distillate yield of solar still, but the most effective one has been the utilization of phase change material (PCM) [6]. For decades, freshwater availability has always remained an utmost concern. According to a report published by World Resources Institute [7], countries like India, Pakistan, the Gulf States, and those at the developing stage face immense challenges (greater than 80 %) in providing fresh water to their populations. A list of countries with their respective freshwater production challenge is depicted in Fig. 1 [7].

Solar still is a beneficial technique in converting impure water into drinkable water, especially in arid areas [8]. It can also be adopted in different circumstances where water treatment is necessary and can undergo various modifications, thus making it suitable for small to medium-sized families. Solar still represents a cost-effective and eco-

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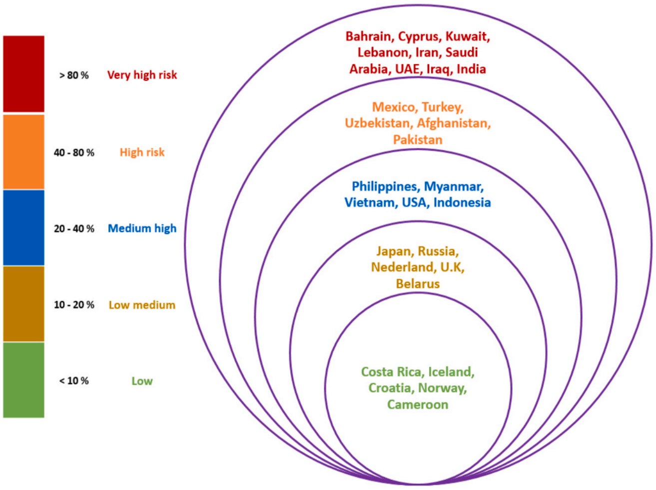
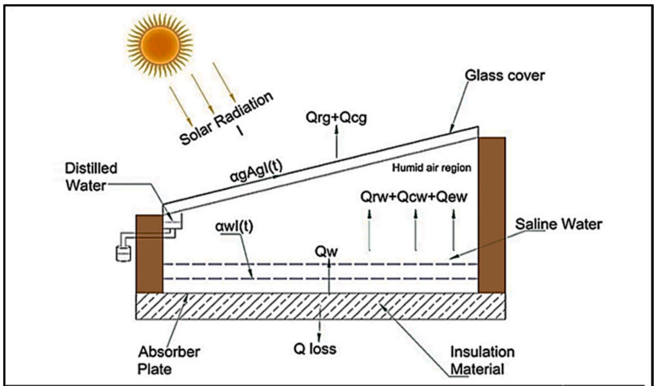


Fig. 1. Countries with a shortage of freshwater.

friendly method that relies on solar energy for its operation. Since the energy input is solar energy, its distillate yield fluctuates depending on solar availability. The distribution of solar energy within the solar distillation system is critically important and must be optimized to ensure maximum energy utility with minimal losses. As illustrated in Fig. 2, some amount of solar energy is utilized directly for evaporation, while some percentage is lost through convection. The incorporation of PCM can effectively reduce these convection losses. Losses occurring from the bottom and side walls can be managed by integrating insulation from the outer surface [9]. The remaining losses occur at the glass surface, which is influenced by the characteristics of the glass material and its surface properties.

Therefore, the present study provides a comprehensive analysis of the influence of various organic PCMs, including paraffin and non-paraffin types, and different integration methods on the performance of various solar still designs. Although the use of PCMs in solar desalination has been examined in earlier publications, these evaluations often concentrate on certain PCM types or a small number of solar still designs. In contrast, the present study adopts a systematic approach, examining PCM classification, selection, compatibility, and their impact on distillate yield across different solar still designs. This study also provides an economic analysis of active and passive solar stills integrated with PCMs to broaden the viability across different solar still configurations. The environmental analysis, crucial for the sustainable application of PCM, has been conducted to assess its effects following the integration of the solar still. By considering these factors collectively, this review provides deeper insights into optimizing PCM selection and integration for various solar still applications. Lastly, a well-structured discussion is presented, followed by conclusions and key recommendations for future research directions.



I = Solar Intensity, α_g = Absorptivity of glass, A_g = Area of Glass, Q_{rw} = Radiative heat transfer from water to glass surface, Q_{cw} = Convective heat transfer from water to glass surface, Q_{ew} = Evaporation heat transfer from water to glass surface, Q_w = Rate of Energy transfer from basin to water, α_b = Absorptivity of basin, Q_{rg} = Rate of energy lost by radiation, Q_{cg} = Rate of energy lost by convection.

Fig. 2. Distribution of energy within solar still [9].

2. Working principle of PCM

The initiation of utilizing PCM in solar still was started in the late 90 s. Since then, the vitality of PCM has been explored by several researchers worldwide [10]. PCMs can absorb heat during peak solar intensity load, and they can release heat when the fluctuation of heat prevails due to unfavourable weather conditions [11]. This heat supplied by PCM can overcome the fluctuation of the energy provided to saline water and enable continuous evaporation in solar still [12]. The schematic diagram of the solar still integrated with PCM is illustrated in Fig. 3a. The PCMs are positioned beneath the water basin to capture heat and transfer it to the water when sunlight is unavailable. Considering the requirement of the mechanism, the transfer and storage of heat by the PCM contributes to the overall increase in the efficiency of solar still. The valuable property of PCMs is their ability to undergo phase transitions (solid–liquid-gas), which occur isothermally during energy absorbed or released [13]. The working mechanism of PCMs, where they change phase from one state to another and concurrently exchange heat with the system, can be understood from Fig. 3b. Hence, it can also act as a thermal reservoir during the execution of thermal cycles [14]. Therefore, its ability to store thermal energy is among many solutions for the prevailing energy storage challenges in solar still [15].

PCMs operate based on the principle of expansion and contraction resulting from variations in the heat they absorb. The relationship between the energy storage capacity of PCM and its volume is inversely proportional; as one increase, the other decreases. In order to finalize a thermal cycle, a standard PCM exhibits a volume change of under 5 % [16]. PCM undergoes two processes simultaneously: sensible and latent. The sensible heat is retained in the PCM without undergoing any phase transition, as can be calculated using Eq. (1). The energy accumulated during a phase transition, specifically the energy stored during a phase change, is directly related to the mass of the material and the constant latent heat enthalpy. The calculation can be performed using Eq. (2) [17].

$$Q_{(sensible)} = mC_p\Delta T \tag{1}$$

$$Q_{(latent)} = mL \tag{2}$$

The system's total energy consists of sensible heat (before phase change) and latent heat (after phase change), represented in Fig. 4, and can be calculated using Eq. (3).

$$Q_{(LHS)} = mC_p\Delta T + mL + mC_p\Delta T \tag{3}$$

Where 'Q' denotes the amount of heat stored by the material, 'm' denotes the mass (kg), and 'L' represents the enthalpy (kJ/kg) during the period of phase change in PCM [18].

3. PCM selection criteria

Apart from solar still, PCMs are utilized in various other applications, such as solar water heating, space heating and cooling, solar cooker and many more.

For instance, Palanikumar et al. [19] developed and evaluated three types of solar box cooker (SBC): with PCM, nano PCM, and without PCM. The blend of waste cooking oil and $C_4H_4O_3$ was utilized to prepare the novel PCM. The nano PCM-integrated SBC, using $MgAl_2O_4/Ni/Fe_2O_3$ nanoparticles, achieved a thermal performance enhancement of 11 % and efficiency up to 56.21 %. Under solar radiation of 1037 W/m^2, it

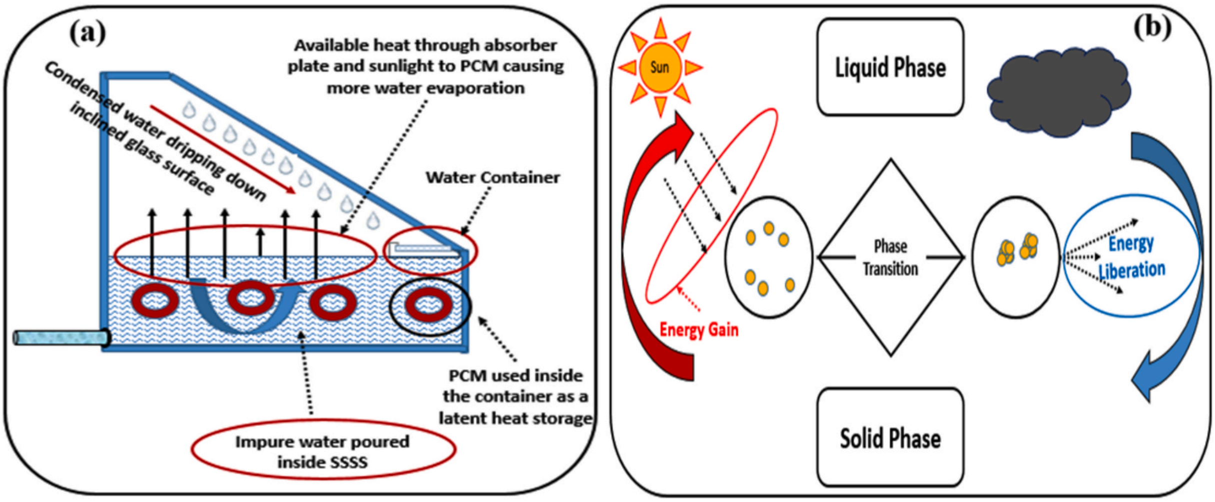


Fig. 3. Schematic layout (a) Working of single slope solar still (SSSS) with PCM (b) Inside view of the working of PCM.

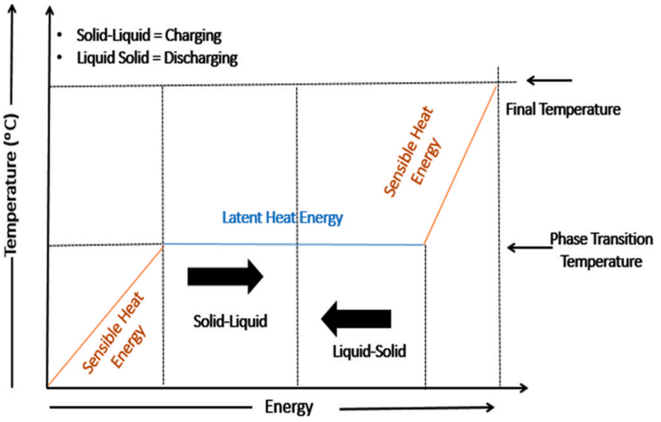


Fig. 4. PCMs store energy during charging and discharging.

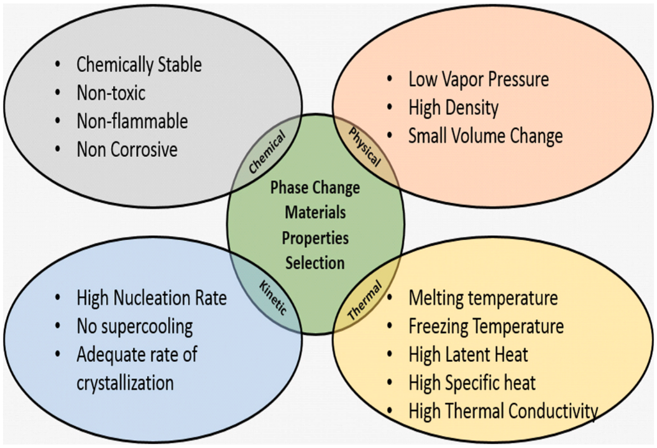


Fig. 5. Critical selection criteria of thermal energy storage materials based on physical, thermal, kinetic, and chemical properties.

reached a maximum internal temperature of 164.12 °C, demonstrating superior performance compared to the other SBC. Furthermore, studies [20,21] enhanced the thermal energy efficiency of the solar cooker by incorporating nanoparticles for better performance. However, the criteria for identifying an appropriate PCM for the application remain unclear. Notwithstanding the ascertained fact, many essential properties must be examined to determine whether a certain PCM should be used. The parameters mentioned include physical, thermal, kinetic, and chemical properties, as seen in Fig. 5. From a physical standpoint, a PCM should possess a low vapour pressure and high density and demonstrate minor volume alteration throughout solidification and melting. From a thermal perspective, the material should have a broad spectrum of melting and freezing temperatures, a high specific heat, a substantial capacity for storing latent heat, and efficient thermal conductivity. Chemically, the kinetic energy within the molecules of PCM is also considered an essential factor: whether molecules are stable or not at different ranges of operating temperatures, not toxic to the environment, non-flammable, and it must be non-corrosive. The PCM should possess a high nucleation rate, phenomena of sudden cooling must be absent, and an adequate rate for crystallization [22].

4. Classification of PCM

PCMs have a long history of utilization in solar still due to their various favourable properties. It possesses all the characteristics required for enhancing solar still yield during the day and night [23]. Broadly, PCMs are classified into four categories: solid–liquid, liquid–gas, solid–solid, and solid–gas, as represented in Fig. 6. Regarding solar still, utilization of solid–solid and solid–gas PCMs is usually not preferred due to the deficient latent heat of enthalpy and poor compatibility [24]. Due to sudden expansion in liquid–gas PCMs, equipment damage can be encountered if utilized in solar still, as reported earlier [25]. The most appropriate PCM for solar still is solid–liquid type due to its ability to store high energy, attributed to its highly stable chemical structure [26], also classified in Fig. 7.

The solid–liquid PCM can be categorized into the following: organic, inorganic, and eutectics, as represented in Fig. 7. It can be observed in Fig. 7 that eutectic PCMs are high in cost and exhibit high melting and solidification temperatures (unfavourable to solar still). In addition, the issue of leakage during the phase transition of eutectic PCMs is prevalent and hence unsuitable in solar still applications [27]. On the other hand, inorganic PCMs are susceptible to corrosion and can deteriorate the metal surface of the water basin, leading to periodic damage to the solar still container surface. Although inorganic PCMs are cost-effective and can store high heat, their inclusion in solar panels is still avoided due to their low compatibility with the storing material [28]. What fascinates is the organic PCM, particularly paraffin, which fulfils almost all the requirements that qualify it for its utilization in solar still. It is cheap, nontoxic, has high compatibility, can be melted at low temperatures (a prime requirement for PCM during the operation of solar still), and has

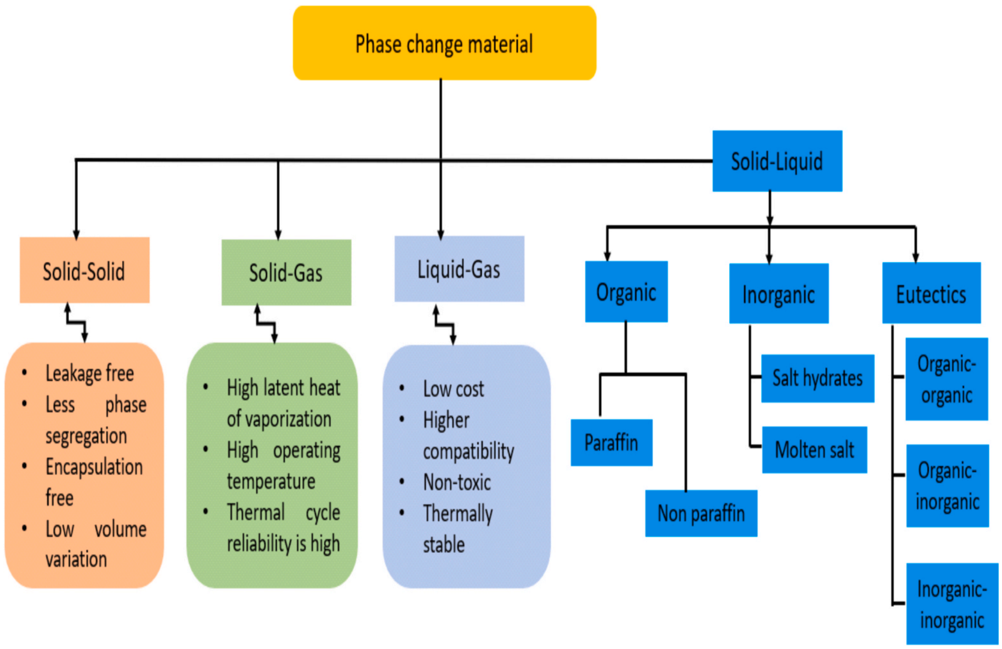


Fig. 6. Types of PCMs.

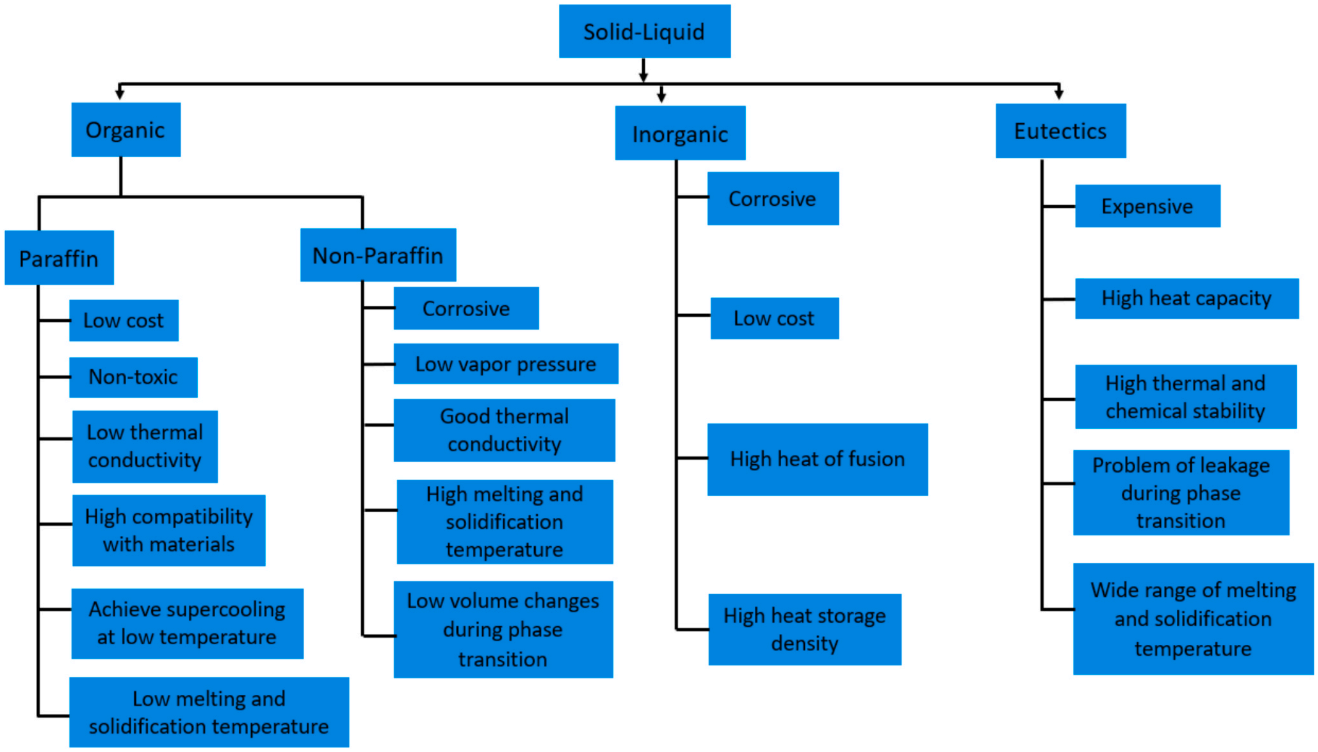


Fig. 7. Typical properties of solid–liquid PCM.

good compatibility with a wide range of materials [29]. Regarding non-paraffin, it has high thermal conductivity and low vapor pressure, which are favourable for improving solar still performance. However, due to its high affinity towards air and moisture, it shows corrosive characteristics and hence is not recommended for solar still operations [30].

Organic PCMs consist of carbon-hydrogen chains ranging from 14 to 40 carbons. It can be derived from nature in the form of waxes, oils, fatty acids, and poly-glycols and offers various advantages such as non-corrosive, low super-cooling, better nucleation rate, thermally and chemically stability, and adjustable phase transition zone as per the desired application [31]. Additionally, certain traits of organic PCMs, including low melting heat, fewer thermal cycles, reduced density, and low thermal conductivity, may not be advantageous for solar stills but are beneficial for other uses such as building construction, transportation, and heat storage [32]. An inorganic PCM, especially salt hydrate, undergoes phase change during the dehydration reaction, which is undesirable in solar still applications because it can severely affect the evaporation rate. The inorganic PCM is non-flammable and has several positive attributes, such as high thermal conductivity, high enthalpy, and low volume changes during phase transition [33]. However, the undesirable melting of the inorganic PCMs may result in phase segregation and lead to poor performance due to the inability to undergo complete thermal cycles [34]. Furthermore, the inorganic PCMs have poor nucleating properties, which results in super-cooling of the liquid phase before crystallization. Adding to this, the inorganic PCMs have a corrosive nature, which decreases their compatibility with the materials, and their high cost does not justify their utilization in solar still [35]. When organic and inorganic PCMs are combined, the resultant thus formed is eutectic PCM. It is a homogeneous mixture of two or more PCMs to obtain desirable properties. Various types of PCMs have a wide range of applications [36]. Long-term stability, high phase change stability, high chemical stability, and surface tension are characteristics of eutectic PCM. However, it is not applied in trivial industries due to its high cost. Table 1 presents a comprehensive overview of the various essential characteristics of different types of PCM. Broadly, PCMs are classified into two groups: organic and inorganic. Organic PCMs are further classified into three subgroups called: (a) paraffin, (b) fatty acids and (c) natural. After carefully examining Table 1, it is evident that paraffin exhibits the broadest operating temperature range among all the tabulated PCMs, an essential property for PCMs to be utilized for solar distillation applications.

Table 1 reveals that paraffin exhibits the highest latent heat of enthalpy at 351.7 kJ/kg, closely followed by barium hydroxide octa hydrate at 332 kJ/kg. In conclusion, a high latent heat enthalpy results in a significant capacity for energy storage, making it ideal for a wide range of heat exchange system applications. The density of PCM plays a crucial role in operating a heat exchange system. A higher-density PCM requires a reduced surface area for efficient heat transfer. In these situations, utilizing PCM with higher density, mainly inorganic PCM is advantageous as it minimizes transportation costs. Comparison of thermal conductivity among various types of PCMs is presented in Table 1. It is noteworthy that the average thermal conductivity of inorganic PCMs significantly exceeds that of organic PCMs, thereby expanding its potential applications in heat exchange systems. However, when comparing the affinity of inorganic PCM for oxidation, it is observed to be greater, which is quite undesirable due to the increased likelihood of corrosion resulting in material degradation.

The preceding discussion indicates that solar stills utilizing organic PCMs tend to provide specific benefits compared to those employing inorganic PCMs or alternative thermal storage options. Organic PCMs exhibit superior thermal stability, reduced corrosion risks, and a more uniform phase change temperature when contrasted with inorganic PCMs, which may encounter challenges such as supercooling or degradation over time. Organic PCMs frequently exhibit a greater latent heat capacity, enabling them to store and release increased amounts of thermal energy, which enhances their effectiveness in stabilizing temperature amidst varying solar radiation. In contrast, inorganic PCMs may exhibit superior thermal conductivity, which could facilitate quicker heat transfer; however, they might necessitate more meticulous oversight owing to their potential instability and reduced safety margins.

Choosing the right PCM is essential for achieving optimal performance in solar distillation. The PCM must exhibit a transition temperature range from 40 °C to 80 °C, which is consistent with the operational parameters of a solar still. To enhance the absorption and storage of peak thermal energy, it is essential for the PCM to have a high latent heat storage capacity. Furthermore, possessing a high thermal conductivity is crucial for improving the heat transfer rate in the basin water, thereby facilitating effective energy distribution. An elevated specific heat capacity is advantageous, as it aids in managing the charging and discharging rates of the solar still, resulting in enhanced thermal efficiency and overall performance. Additionally, the PCM should not leave any harmful traces to the environment during discharge.

5. Compatibility of PCM with storing container

Metals have low corrosion resistance, which results in progressive deterioration of their structure, diminished performance, and increased safety risks. To tackle this problem, industry standards have established norms for acceptable corrosion rates (measured in mm/year or mg/cm^2.year) within materials [137]. The corrosion rate is calculated using Eq. (4). According to literature, the long-term use is strongly encouraged for materials with corrosion rates below 10 mg/cm^2.year, whereas materials with rates between 10 mg/cm^2.year and 49 mg/cm^2.year might be used cautiously in some applications. Solar stills should not be constructed using very corrosive materials, defined as having a corrosion rate of 50 mg/cm^2.year or above. Experimental studies suggested that a container made of copper shows the development of pitting when immersed in a solution of salt-hydrated PCM with PlusICE (E17) and ClimSel (C18) [138]. In addition, the formation of a copper oxide layer was also noticed at the surface of copper. On the other hand, when aluminium is immersed in the same solution, corrosion occurs in the form of galvanic pitting [139]. The aluminium surface was adorned with fissures of varying sizes, both large and small. The average pit size was 20–160 μm upon microscopic examination, with a maximal pit size of 650 μm [140]. According to recent reports, grain boundaries provide a protective barrier for copper material containers used with paraffin wax PCM, reducing the corrosion rate with time. Corrosion rates of 26.65 mg/cm^2.year, 13.08 mg/cm^2.year, and 7.95 mg/cm^2.year were recorded after 10, 30, and 60 days of testing at 80 °C, respectively [141].

$$\text{Corrosion rate} = \frac{\text{Specimen initial mass (mg)} - \text{Specimen final mass (mg)}}{\text{Test time frame (year)} \times \text{Specimen area (cm2)}} \tag{4}$$

It is crucial to thoroughly assess its corrosion resistance qualities while selecting a PCM for a particular application [142]. Materials with a low tendency to corrode are more desirable because they provide increased durability and a longer lifespan [143]. Therefore, it becomes mandatory to consider many elements, such as the surrounding environment, temperature fluctuations, chemical exposure, and mechanical strains [144]. Storing PCMs within a container increases the likelihood of long-term deterioration because of chemical and electrochemical processes between the container surface and the PCM [145,146]. Corrosion of metals by PCMs may primarily appear in three distinct ways [147]:

- Metal oxidation: oxidation of metals occurs when PCM gradually corrodes the porous outer layer of the container, resulting in even and consistent perforation. This is characteristic of materials such as mild steel.
- Pitting: Corrosion begins at a particular location, becomes more severe, and forms deep “pits.” This phenomenon is often found in metals that have been coated, such as pinholes, stainless steel, and aluminium.
- Stress crack corrosion: Corrosion develops in regions experiencing stress, causing sudden failure. This is prevalent in stainless steel materials.

The effect of corrosion on the container surface must be mitigated. Thus, it is imperative to thoroughly understand the mechanisms of corrosion and its controlling factors [148]. Thermal stability of the material, surface roughness, and applied coatings are essential factors that decide the compatibility between the PCMs and the container materials [34,149]. Materials such as aluminium, copper, brass, and stainless-steel are viable alternatives to conventional container materials used with PCMs because of their utility for thermal energy storage and longer service life [150].

Table 1
Properties of solid–liquid PCMs.

Group	Compound	Chemical formula	Phase change temperature (°C)	Latent heat (kJ/kg)	Density (kg/m^3)	Thermal conductivity (W/m-K)	Specific heat (KJ/kg-K)	Ref.	Applications
Organic PCM-Paraffin $CH_3–(CH_2)_n-CH_3$	n-Dodecane	$C_{12}H_{26}$	−11.85	216	863 (S), 736 (L)	0.21 (S)	–	[37,38]	Constructions, solar thermal energy storage, electronics cooling, transportation industry, medical and pharmaceutical cold chain.
	n-Tridecane	$C_{13}H_{28}$	−5.85	160	756 (L)	0.21	–	[37]	
	n-Tetradecane	$C_{14}H_{30}$	6.15	230	884 (S), 758 (L)	0.21 (S)	–	[37,38]	
	n-Pentadecane	$C_{15}H_{32}$	10.15	207	861 (S), 769 (L)	0.17	–	[37,38]	
	n-Hexadecane	$C_{16}H_{34}$	18.15	238	864 (S), 773 (L)	0.21 (S)	–	[37,38]	
	n-Heptadecane	$CH_3(CH_2)_{15}CH_3$	18.35——22.15	215–240	778	0.39	2.233	[37,39]	
	n-Octadecane	$C_{18}H_{38}$	27–28.5	243.5–245	855 (S), 777–860 (L)	0.35 (S), 0.15 (L)	1.91–2.14 (S), 2.66 (L)	[37,38,40]	
	RT-21		21	155	880 (S), 770 (L)	0.2 (L, S)	2 (L, S)	[40,41]	
	RT22HC		22	190	760 (S), 700 (L)	0.2 (L, S)	2 (L, S)	[40,41]	
	RT24		24	160	880 (S), 770 (L)	0.2 (L, S)	2 (L, S)	[40,41]	
	RT-25		25	170–230	880 (S), 760 (L)	0.2	2	[42,43]	
	RT-25HC		25	230	880 (S), 770 (L)	0.2 (L, S)	2 (L, S)	[40,41]	
	RT-28HC		28	250	880 (S), 770 (L)	0.2 (L, S)	2 (L, S)	[40,41]	
	RT-31		31	165	830 (L, S)	0.2 (L, S)	2 (L, S)	[40,41]	
	RT35		35	160–220	860 (S), 770 (L)	0.166, 0.2 (L, S)	2 (L, S), 2.1	[40,41,44]	
	RT35HC		35	240	880 (S), 770 (L)	0.2 (L, S)	2 (L, S)	[40,41]	
	RT-27		25–28	179	800 (@15 °C)	0.2	2	[45,46]	
	RT-42		38–43	174	880 (S), 760 (L)	0.2	2	[47]	
	RT44HC		41–44	250	800 (@25 °C)	0.2	2	[46,48]	
	RT-50		45–53	160–182	880 (S), 760 (L)	0.2–0.3	2.01	[49,50]	
	RT54HC		53–54	200	850 (@25 °C)	0.2	2	[46,47]	
	RT-82		77–85	176	950 (S), 770 (L)	0.2	2	[51,52]	
	Paraffin wax	CnH_{2n+2}	32–67	81.81–351.7	920–930 (S), 770–870 (L)	0.51 (S), 0.22 (L)	1.92–2.967 (S), 3.26 (L)	[41,53–55]	
	A32		32	130	845	0.21	2.2	[56]	
	A39		39	105	900	0.22	2.22	[56]	
	A42		42	105	905	0.21	2.22	[56]	
	A48		48	234	810	0.18	2.85	[56,57]	
	A53		53	130	910	0.22	2.22	[56]	
	A55		55	135	905	0.22	2.22	[56]	
	A58		58	132	910	0.22	2.22	[56]	
	A62		62	145	910	0.22	2.2	[56]	
	Petroleum jelly		36–60	220	849.9	0.18	2.96	[58,289]	
	Vaseline		25–39	196	879 (S), 822 (L)	0.205	2.05 (S), 2.1 (L)	[59,180]	
Organic PCM-Fatty Acids $CH_3–(CH_2)_n-COOH$	Lauric acid	$C_{12}H_{24}O_2$	41–44	178–222.3	1007 (S), 880 (L)	0.45 (S), 0.15 (L)	1.6–2.34 (S), 2.17–2.53 (L)	[60,62,106,206,265]	Food packaging, refrigeration and air conditioning, energy storage, building materials, Thermal energy storage, solar energy applications, electronic cooling, automotive thermal management.
	Myristic acid	$C_{14}H_{28}O_2$	45.71–56	173.46–252.92	990 (S), 862.2 (L)	0.15–0.2	1.7–2.8 (S), 2.4–2.75 (L)	[60,63–65,263,265,274]	
	Capric acid	$C_{10}H_{20}O_2$	32	152.7	1004 (S), 878 (L)	0.37 (S), 0.14 (L)	1.9 (S), 2.1 (L)	[41,65]	
	Stearic acid	$C_{18}H_{36}O_2$	59.88–70.12	170–259	965 (S), 848 (L)	0.172–0.341	1.6–2.53 (S), 2.2 (L)	[61,65–68,216]	
	Palmitic acid	$C_{16}H_{32}O_2$	54–64	185.4–241	989 (S), 850 (L)	0.162–0.28	2.1–2.2 (S), 1.9–2.56 (L)	[61,65,68,207,264,265]	
	Palmityl palmitate		57.21	259.19	858	0.3432	–	[69,70]	
	Methyl palmitate		27.39	243	857.10	0.28	–	[71,72]	
	Capric-Stearic acid		28.75	165	–	0.231	–	[73]	
	Lauric-Stearic acid		29.78–43.77	121.8–193.7	–	0.211–0.2879	1.92 (S), 2.10 (L)	[74–77]	

(*continued on next page*)

Table 1 (*continued*)

Group	Compound	Chemical formula	Phase change temperature (°C)	Latent heat (kJ/kg)	Density (kg/m^3)	Thermal conductivity (W/m-K)	Specific heat (KJ/kg-K)	Ref.	Applications
	Myristic-Capric acid		18.15–24.63	139.8–168.37	–	0.27	1.97 (S), 2.31 (L)	[78,79]	
	Palmitic-Stearic acid		53.37–54.24	183–194.46	845 (S)	0.205, 0.26	2.40 (S), 2.50 (L)	[78,80,81,208]	
	Lauric-Capric acid		18–28.3	133.7–142.2	900 (S), 894.9 (L)	0.139 (S), 0.143–0.271 (L)	2.24 (S), 1.97 (L)	[82–84]	
	Capric-Palmitic acid		22.4–27.48	127.8–195	870 (S), 790 (L)	0.143–0.22	2 (S), 2.3–2.4 (L)	[56,84–87]	
	Lauric-Myristic acid		32.04–34.34	158.88–177.65	–	–	2.54 (S), 2.40 (L)	[78,88]	
	Palmitic-Lauric acid		35.95–39.57	171.65–182.54	1050	0.18–0.24	2.03	[89,90]	
	Myristic-Stearic acid		45.62–47.13	153.3–196.21	–	0.24	–	[207,266]	
	Myristic-Palmitic acid		45.25–59.89	127.94–190.99	–	0.225	–	[91,92]	
	Lauric-Palmitic-Myristic acid		28.27–32.24	160.41–177.43	–	0.2528	–	[88,93]	
	Capric-Myristic-Palmitic acid		17.7	148.7	–	0.149	–	[94]	
	Myristic-Palmitic-Stearic acid		41.72	163.5	–	0.25	–	[95]	
	Lauric-Palmitic-Stearic acid		32.1	151.6	–	0.21	–	[96]	
	Capric-Palmitic-Stearic acid		18.90	147.2	850.9	0.3407	–	[97]	
Organic PCM-Natural	Bees wax		51–62.28	145.62–214 (S), 141.49 (L)	819.75–970 (S), 789.47–811 (L)	0.231–0.25	2.081	[98–100]	Antimicrobial activity, thermal energy storage, electronic cooling, building and construction, automobile l application, solar thermal application.
	Shellac wax		51.1–81.5	148–203.2	945–965 (S), 813.3 (L)	0.29–0.33 (S), 0.3–0.31 (L)	1.9–2.1 (S), 2.1–2.3 (L)	[100,101]	
	Carnauba wax		80–88	168.3–206	970–998	0.12–0.3403 (S)	1.98 (S)	[100,102,103]	
	Coccerin wax		85.78	193.2	–	–	–	[104]	
	Insect white wax		84.82	180.7	–	–	–	[104]	
	Candelilla-wax		69–73	149	–	–	–	[105]	
	Ricebran-wax		78–82	180	–	–	–	[105]	
	Berrywax		50–54	99	–	–	–	[105]	
	Sunflower wax		74–78	192	–	–	–	[105]	
	Soy wax		30.9–54.2	67.6–117.60	900–1156 (S), 825–1146 (L)	0.324 (S), 0.1573 (L)	4.96 (S), 2.06 (L)	[106,107,180]	
	Palm wax		56.96	149.1721	1155 (S), 1145 (L)	0.1550 (S), 0.1565 (L)	2.02 (S), 2.892 (L)	[108,109]	
	Sheep fat		48.2	183	916 (S), 828 (L)	0.325	2.06 (S), 2.06 (L)	[110]	
Inorganic	Calcium chloride tetrahydrate	$CaCl_2{\cdot}4H_2O$	39–44.2	99.6–158	1566.6–1830	–	1.34	[109,111]	High-temperature thermal energy storage, heat transfer fluids, building applications, thermal barrier coatings.
	Calcium chloride hexahydrate	$CaCl_2{\cdot}6H_2O$	20–31.2	154.7–201	1710–1800 (S), 1496–1530 (L)	1.09 (S), 0.54–0.6016 (L)	1.40–2.18 (S), 2.20–3.25 (L)	[40,112–114]	
	Calcium nitrate tetrahydrate	$Ca(NO_3)_2{\cdot}4H_2O$	42.3–47	131–153	1820 (S)	0.5749	1.46 (S)	[115–117]	
	Lithium nitrate triydrate	$LiNO_3{\cdot}3H_2O$	29.6–31.9	283–296	1575–2140(S), 1425 (L)	0.58–1.32	1.73–2.77	[115,118,119]	

(*continued on next page*)

Table 1 (*continued*)

Group	Compound	Chemical formula	Phase change temperature (°C)	Latent heat (kJ/kg)	Density (kg/m^3)	Thermal conductivity (W/m-K)	Specific heat (KJ/kg-K)	Ref.	Applications
	Sodium sulfate decahydrate	$Na_2SO_4 \cdot 10H_2O$	32–33	180–254	1400–1600	0.544–0.56 (S), 0.45 (L)	1.55–2.09 (S), 3.31–3.78 (L)	[115,116,120–123]	
	Zinc nitrate hexahydrate	$Zn(NO_3)_2 \cdot 6H_2O$	34.4–36.4	130–152	1979–2070 (S), 1760 (L)	0.46–0.7	1.34 (S), 2.26 (L)	[117,118,125–128]	
	Sodium hydrogen phosphate dodecahydrate	$Na_2HPO_4 \cdot 12H_2O$	35–37	227–280	1520 (S), 1446 (L)	0.51 (S), 0.48 (L)	1.48–1.69 (S), 1.94–3.91 (L)	[41,123,124,127]	
	Sodium thiosulfate pentahydrate	$Na_2S_2O_3 \cdot 5H_2O$	48–55.2	200–210	1690–1750 (S), 1666–1670 (L)	1.153	1.46 (S), 2.38 (L)	[115,124,128,129]	
	Sodium acetate trihydrate	$CH_3COONa \cdot 3H_2O$	58–64	226–290.47	1450 (S), 1280 (L)	0.57 (S), 0.4809 (L)	2.13 (S), 3.35 (L)	[115,130–133]	
	Sodium carbonate decahydrate	$Na_2CO_3 \cdot 10H_2O$	31–36	210–267	1440–1460 (S)	0.544–0.79 (S), 0.224 (L)	1.88–2.10 (S), 3.15–3.35 (L)	[112,115,116,120,123]	
	Barium hydroxide octahydrate	$Ba(OH)_2 \cdot 8H_2O$	78	233–332	2070–2180	0.86–1.1624	1.817	[115,134–136]	

6. PCM in solar still

6.1. Solar distillation

The availability of fresh water for the commoner has remained challenging for most developed countries. As a result of increased globalization and population, the demand for fresh water at the end of 2050 is expected to rise by more than half of the total present demand [151]. Fresh water resources are limited and vary in quantity, depending on the climatic and geographic conditions. On the contrary, ocean water is infinite but not feasible for drinking, but it can be processed and converted into fresh water [152]. To do this, several techniques are available to treat ocean water, such as adsorption [153], flotation [154], nano-filtration [155], electro-coagulation [156], electro-oxidation [157], reverse osmosis [158], and solar distillation [159,160]. The information on the various water treatment methods is tabulated in Table 2. It outlines the operational concept, advantages, disadvantages, and the cost per liter of treated water. The said techniques have recently undergone various necessary developments to obtain higher yields. A graphical representation is shown in Fig. 8 which contains number of articles related to various water treatment techniques published in reputed journals sourced from science direct. Fig. 8 suggests that between 2018 and 2024 research carried out was highest in electro-oxidation i.e., 48.6 % share of total available publications followed by reverse osmosis (32.2 %). Solar distillation articles account for 8.85 % of total published articles in the same duration.

Additionally, it includes remarks based on insights from previous literature. It can be observed that solar distillation has a simple operational principle compared to other techniques. However, different methods can desalinate a higher amount of water compared to solar distillation. Yet, water wastage and the high initial and operating costs of these techniques are uneconomical compared to solar distillation for domestic purposes. Thus, solar distillation is more practical in desalinating water than other methods. It is simple, practical, low cost, environment friendly, and works on the principle of evaporation and condensation [161]. However, its demerit is low productivity or even zero at midnight. Perhaps, the day-night productivity of the solar still can be enhanced by modifying the design of the solar still, e.g., single slope solar still (SSSS) [162], double slope solar still (DSSS) [163], pyramid solar still (PSS) [164], triangular pyramid solar still (TPSS) [165], stepped solar still (SSS) [166], tubular solar still (TSS) [167,168], hemispherical solar still (HSS) [169], tilted wick solar still (TWSS) [170] and also with the help of external attachments such as flat plate collector (FPC) [171], evacuated tube collector (ETC) [172], parabolic trough collector (PTC) [173], heat exchanger (HE) [174], photovoltaic thermal (PVT) [175], condenser [176], reflectors [177], tracking sun axis [178] and so on. Shanmugan et al. [179] studied the effect of chemical potential behavior of temperature component on PSS. The authors propose the Gibbs free energy equation to determine the energy shift between the evaporating and condensing phases in a steady state. Furthermore, they indicated a daily average efficiency of 38.135 % with an output of 4.28 *l*/m2.The performance of the pyramid stepped basin solar distiller was found to exceed that of the conventional basin solar distiller. The difference in chemical potential between the two phases during the daily working hours, measured every 30 min, is less than 0.060 J/kg. This means that the solar distiller being studied works in a saturated mode. Ghandourah et al. [180] studied the effect of lanthanum cobalt oxide nanoparticle coated jute wick in DSSS. The experimental results were later validated with Dunkle's correlation. Author reported a significant improvement in distillate yield at lower mass flow rate of saline water over the wick surface. Additionally, the daily productivity of the proposed DSSS coated with and without 20 wt% lanthanum cobalt oxide/black paint was reported 5.40 and 3.85 kg/m^2.day, respectively, at saline water flow rate of 0.05 kg/min. Recently, Kumar et al. [181] blends TiO_2/jackfruit peel composite with the silver balls. The nanoparticle was varied at the concentration of 0.1–0.3 wt% with the system. The author

Table 2
Waste/saline water treatment methods.

Saline water treatment process	Working principle	Merits	Demerits	Treated water cost	Remarks
Floatation [154]	Gas bubbles play an essential role in the removal of impurities	Removal of total suspended solids	High cost, sludge formation, the high initial cost.	–	High maintenance and initial cost limit its usage for domestic purposes.
Nanofiltration [155]	The impure water is passed through an organic materials-based membrane made of polycarbonate and polyimide.	Reduce heavy metals, nitrates, and salts.	High energy consumption, required water pre-treatment, and a high initial cost.	–	High initial cost and high membrane cost limit its utility.
Electrocoagulation [156]	The impure water is treated by providing an electrical current. The wastewater meets a cathode pair; it neutralizes the waste by forming hydroxides.	No chemicals are added, and the Cost of operation is low.	Requires electrodes to feed current, regular cleaning, high maintenance cost	–	High energy consumption and not suitable for domestic use.
Electrooxidation [157]	The impure water is treated by a highly reactive agent such as hydroxyl radical.	Various electrodes can be used; they are cheap and effective in oxidizing pollutants.	Some electrodes, such as PbO_2, are corrosive and have a short life span.	–	Poor efficiency and complex processes make it suitable for industrial purposes.
Reverse Osmosis [158]	Impure water is passed through a semi-permeable membrane	Energy efficient, highly effective	High maintenance cost, removal of minerals, High wastewater	0.024–0.12 $/L	It removes minerals from the treated water that can create significant health problems. Wastewater rejection is high.
Solar Distillation [159,160]	Evaporation and Condensation	Non-polluting, simple working, use sun as an energy source, and 98 % of brine water can be treated cheaply.	Low productivity	0.012–0.059 $/L	Simple construction to treat impure water for small families.

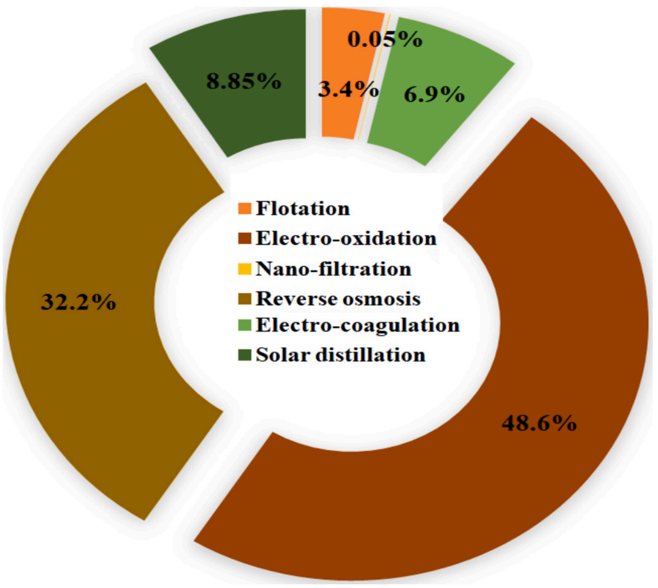


Fig. 8. Share (%) of various researches published for saline water treatment in the past six years (2018–2024) (.
Source: from Science Direct)

reports highest yield of 8.790 l/m^2 at 0.3 wt% nanoparticle concentration blended steel ball composite, revealing the best suitable modification in terms of yield and enviroeconomic analysis. Furthermore, Sangeetha et al. [182], reported highest yield of 14.92 l/m^2.day with daily efficiency of 38.73 % for double slope U shaped basin solar still coated with ZMC (Z = ZnO, M = Mangifera Indica, C=Celostia Argentea) nanoparticles blended with black paint. The author recommended design due to a significant improvement in yield compared to conventional design. Apart from this, solar stills often experience significant heat transfer losses, which can be mitigated by incorporating PCM [183–187].

6.2. *Role of PCMs in solar distillation*

Due to high heat loss in solar stills and limited availability of solar radiation, the distillate output produced by solar stills often observed to be reduced by a significant margin. According to the study, a small amount of energy is used by solar still, and the rest is rejected in the form of various losses, as shown in Fig. 2 [9]. Recent findings suggest that the losses occurred in solar still can be minimized up to a to a certain level by providing low thermal conductivity insulating materials at the bottom of solar still or using large energy storing capable PCMs. Eventually, encapsulating PCMs in solar stills is more beneficial than insulating materials. Utilization of PCM in solar still applications is not new in fact; it has substantial contribution in the enhancement of productivity or yield of solar still. From the evidences obtained from recent published data it has been learned that utilising PCM in solar still can bring about half of increase in total desalination output. PCMs ensures the continuous working of solar still even after the presence of sunlight. Having been reported in the recent studies, several types of PCMs have been developed and employed in solar still application to achieve improved output. Besides, incorporating PCM in solar still is beneficial in reducing the cost of desalination of impure water. Also, utilization of PCM can significantly mitigate the carbon foots. Therefore, a comprehensive examination of various types of PCM utilised in solar still has become inevitable that would be helpful to establish an understanding of PCM influence on solar still.

6.3. *Non-paraffin (organic PCM) with various solar stills*

Fatty acids are obtained from animals and vegetables as triglycerides and hydrates of acids of triglycerides [188]. Several techniques are available to process and refine organic PCM, e.g., fractionation and transesterification, hydrogenation and transesterification, isomerization, and transesterification processes [189]. Its utilization in thermal energy storage applications is pretty advantageous. Sari et al. [190] investigated and confirmed that organic PCM, such as palmitic acid and muriatic acid, were compatible with stainless steel and aluminium made storage containers for solar thermal applications [191]. The thermal characteristics do not allow inorganic PCM to be used in solar still applications due to significant changes in volume in the fatty acid state (palmitic, capric, and caprylic acids) that lead to a lowering in density by a margin of 8–14 % [192,193].

6.3.1. *Lauric acid as PCM in solar still*

Lauric acid, a naturally derived material from fatty acid, can be utilized as PCM for energy storage applications. It is chemically stable with a melting point that falls in the range of 45 °C-50 °C. It is comparably denser and can store higher energy [194]. In solar distillation systems, using lauric acid improves the distillation yield. For instance, Kateshia and Lakhera [195] conducted experiments considering four different cases such as (a) conventional solar still (CSS), (b) solar still with palmitic acid (SSPA), (c) solar still with lauric acid (SSLA), and (d) solar still with stearic acid (SSSA), as shown in Fig. 9a.

The study found that in January, when the solar distillation system was separately tested with stearic acid, lauric acid, and palmitic acid, the system using lauric acid produced the highest distillate yield, as shown in Fig. 9b, particularly when solar intensity was at its peak. In contrast, during the same experiment conducted in May under similar conditions with the same PCMs, the highest distillate yield was achieved with stearic acid, as presented in Fig. 9b. This variation can be attributed to the differences in the thermal properties of the PCMs. Lauric acid outperforms in winter due to its higher thermal conductivity, specific heat capacity, and lower phase change transition temperature, which are advantageous under lower ambient temperatures. However, in summer, stearic acid delivers better performance because of its higher latent heat enthalpy and higher phase transition temperature, making it particularly well-suited for high-temperature conditions during summer season. It has been learned from the study that a low melting point of PCM was suitable for the winter season, while a higher melting point of PCM shows better distillate output during summer. Besides, the relation between water depth and distillate yield has been observed to be more significant since higher thermal energy was required to increase the temperature for large basin water mass. However, during the night, the sensible heat stored within the water during the daytime and additional thermal energy from PCM help augment the distillate yield. The distillate yield for day and night was increased by 30 % and 127 %, respectively, and the overall distillate yield was improved by 30 %, containing 30 kg of PCM [196]. The study by Chauhan and Shukla [197] focuses on the influence of quantum dot and lauric acid as PCM on conventional and prism-shaped solar stills. With quantum dot and lauric acid PCM, yield improved by 100.1 % in the case of prism-shaped solar still and 83.13 % in the case of conventional solar still compared to without quantum dot and lauric acid PCM. The study by Pandey and Naresh [198] explores the use of a novel PSS in Indian arid regions for desalination. Three experimental setups were designed and fabricated: conventional PSS (case-1), solar still with PCM, and fins (case-2), and solar still with PCM, fins, and ultrasonic fogger (case-3). In comparison to case-1, case-3 showed significant improvements in productivity (143.78 %), energy efficiency (57 %), and exergy efficiency (89.67 %). The cost per liter of freshwater and payback period for case-3 was reduced by 47.36 % and 44.37 %, respectively, compared to case-1.

6.3.2. *Stearic acid as PCM in solar still*

Stearic acid is derived from fatty acids in vegetable oils such as

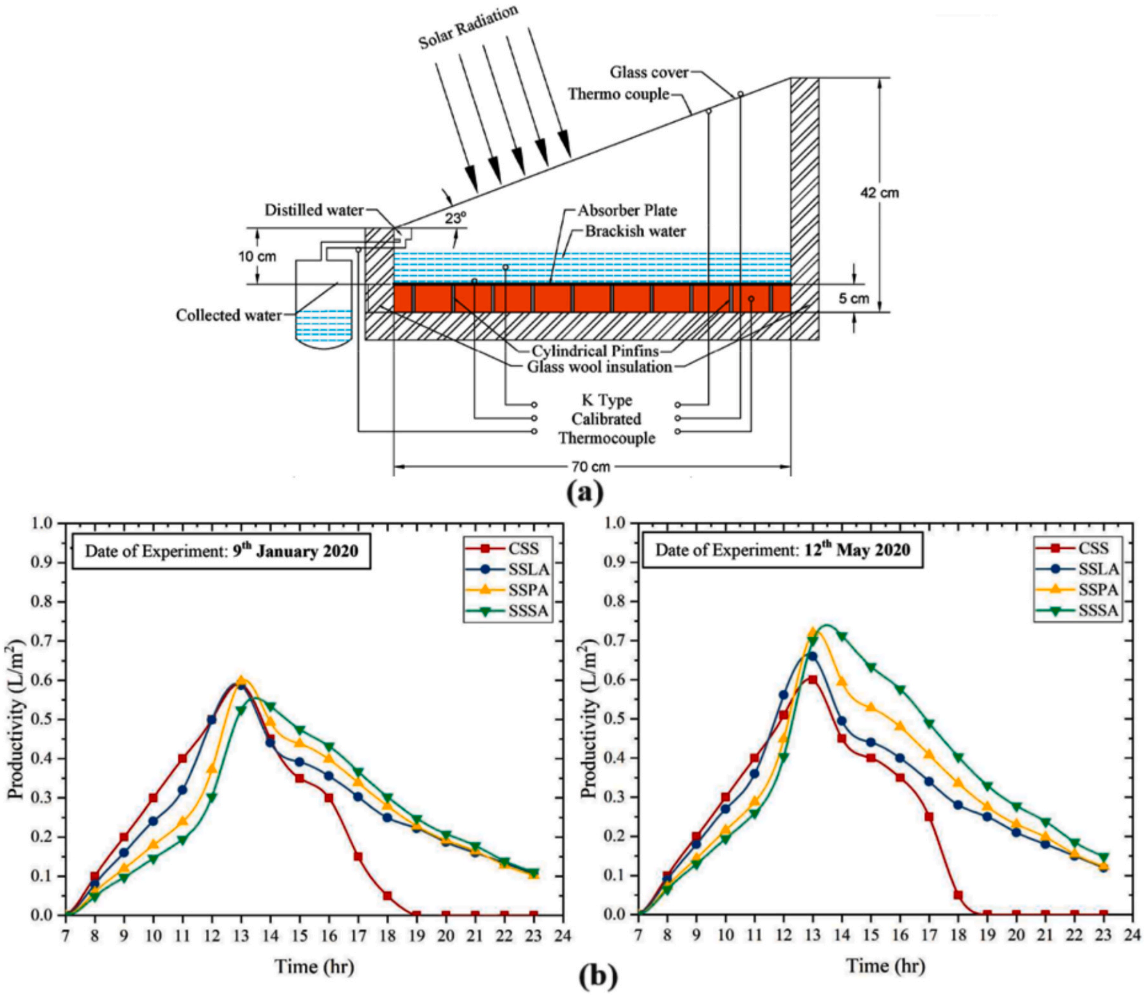


Fig. 9. (a) Schematic of solar still with pin fins and PCM; (b) Hourly productivity variation [195] (Adopted with permission, License number: 5970460609373).

coconut and petroleum [199]. Its ability to store and release thermal energy while exhibiting phase change makes it a suitable material for thermal energy storage. It has a high melting point and heat of fusion working as a PCM has several merits, such as high latent heat of fusion, low cost, and ease of availability [200]. However, it has disadvantages, like low thermal conductivity and a tendency to super cool at a slight temperature difference. Abed and Hachim [201] investigated the effect of stearic acid and paraffin wax on the distillate yield of TSS. Authors claimed that the daily TSS (with PCM) productions for fresh water increased by 9.5 % and 14.39 %, respectively, compared to the daily TSS (without PCM) productions, while using 40 mm thick stearic acid and paraffin wax, respectively. Kumar et al. [202] performed an experimental study on weir-type cascade solar still with three different PCMs, i.e., stearic acid, beeswax, and palmitic acid. Results revealed that high latent heat storage of palmitic acid enhances productivity by 33.69 %, the highest among all investigated PCMs. Kabeel et al. [56] performed a comparative study on the effect of inorganic and organic PCM on solar still. The results revealed the use of stearic acid increases productivity by 65 %. However, among all PCMs, capric-palmitic and A48 show significant improvement in distillate by more than 90 % and reported the environmental effect of inorganic PCMs, which may be restricted in various applications. Toosi et al. [203] performed an experimental study on SSS to increase the distillate yield of solar still. To study the combined effect of the condenser and stearic acid as PCM, the performance of SSSS was investigated using various arrangements such as SSSS (Case I), SSS with an external condenser (Case II), SSS with stearic acid as PCM (Case III), and SSS with external condenser and PCM (Case IV). The schematic diagram of the system is represented in Fig. 10a and the variation in the overall yield throughout the day can be seen in Fig. 10b. It can be clearly observed that during peak hour the simultaneous addition of PCM and condenser resulted in 104 % distillate yield augmentation for Case (IV) compared to conventional one.

6.3.3. *Myristic acid and palmitic acid as a PCM in solar still*

Myristic acid is a saturated fatty acid with a 14-carbon atoms chain [204]. It is commonly found in various natural sources such as palm oil, coconut oil, kernel oil, etc. Myristic acid has shown its potential as a PCM for energy storage due to the high latent heat of fusion and an adequate melting point [205]. The low thermal conductivity limits its usability even though the energy efficiency of SSSS with myristic acid was found to be 34.4 %, including a 42 % boost in distillate yield [206]. The study by Gupta and Solanki [207] investigates the enhancement of water yield in DSSS by embedding eutectic PCM (mixture of stearic acid and myristic acid). In comparison to CSS, the study finds that the addition of PCM to DSSS improved exergy efficiency, energy efficiency, and total cumulative yield, by 72 %, 37 %, and 35.1 %, respectively. Palmitic acid is the most common saturated fatty acid found in plants, animals, and many microorganisms. Palmitic acid is a 16-carbon

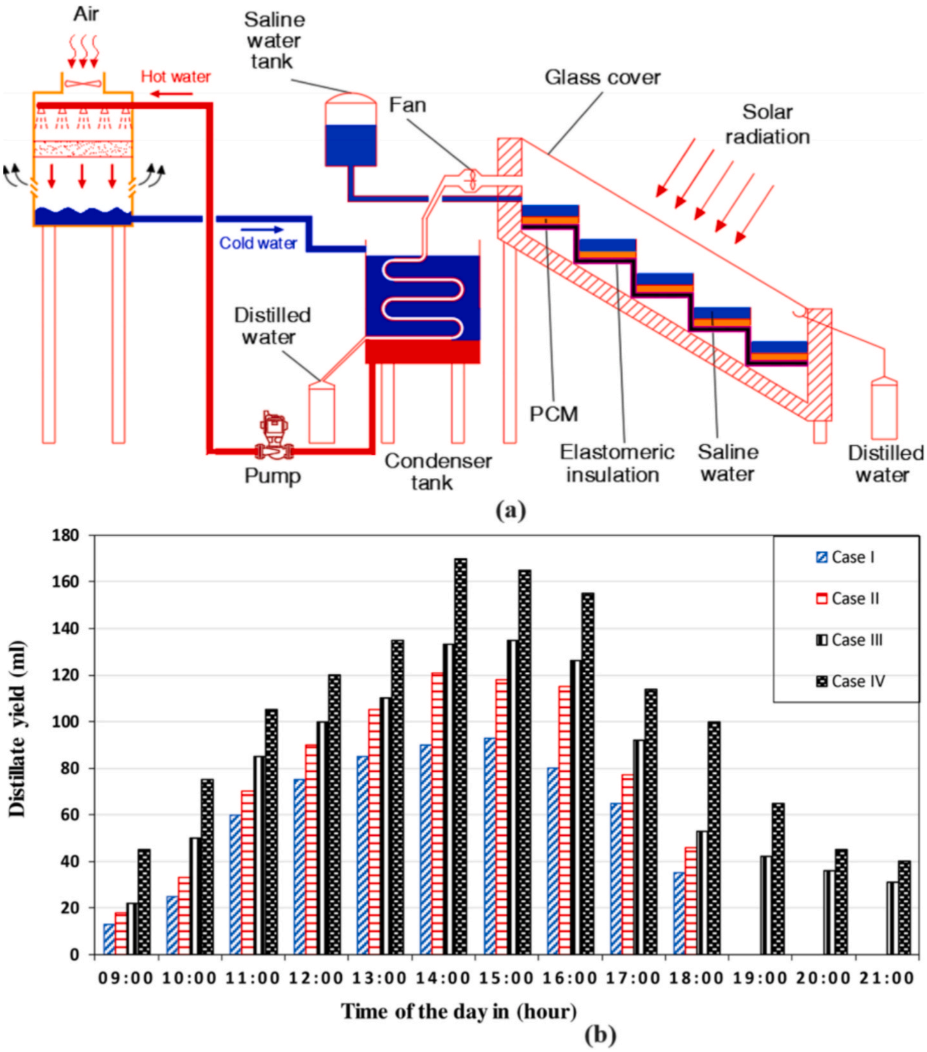


Fig. 10. (a) Schematic of SSS with PCM and external condenser, (b) Distillate yield for various investigated cases [203]. (Adopted with permission, License number: 5970450762679).

saturated fatty acid denoted as n-hexadecanoic acid. It has a melting point of 54–64 °C and latent heat in range of 185.4–214.7 kJ/kg. Major sources of palmitic acid are palm oil, palm kernel oil, coconut oil, and milk fat [208]. Palmitic acid is utilized in solar stills because of its thermophysical properties; however, it has also been noted for its toxic characteristics [267]. In order to compare the efficacy of using palmitic acid as PCM and pin fins in solar stills to a traditional still, Kateshia and Lakhera [209] carried out an experiment. According to their results, the application of PCM and pin fins led to a notable 30 % boost in freshwater production. In another study, Kateshia and Lakhera [210] performed experiment on the solar still with palmitic acid as PCM. According to the findings, using palmitic acid as PCM increased the productivity by 54 % compared to conventional solar still without PCM. The study by Agrawal and Singh [211] focuses on the use of steel wool fibre and binary eutectic (mixture of stearic acid and palmitic acid) PCM in solar still. The total cumulative yield and average energy efficiency for the steel wool and PCM used solar still were 86 %, and 41 %, higher than conventional solar still.

6.3.4. *Other organic PCM including natural waxes used in solar still*

The study by Sharma and Birla [58] reported that the use of petroleum jelly as PCM in solar still showed an improvement of 35.3 % in daily productivity and 20 % increase in heat transfer rates compared to simple solar still. Sharshir et al. [110] investigated the influence of sheep fat as PCM on the performance of solar still. The study claimed that using sheep fat as PCM, the daily productivity and thermal efficiency of the solar still increased by 39.6 % and 45 %, respectively. The study by Amim et al. [174] suggests integrating metallic thermal transfer constituents and beeswax PCM into tubular solar still. The study claimed that the system's efficiency and productivity increased by 54.04 % and 66.18 %, respectively. Tan et al. [183] showed that solar still with petroleum jelly as PCM increases productivity by 39.2 % and efficiency by 42.5 % compared to the still with no PCM. Bisu et al. [212] investigated the effects of beeswax as PCM in solar still performance. Two stills were used, one without a PCM and the other with beeswax as a PCM. The results showed that the experimental still with beeswax as PCM had a 109.30 % improved thermal efficiency compared to the control still without a PCM. The study by Saad et al. [184] investigates the impact of vaseline and soy wax as PCMs on the productivity of solar still. The results showed that using 1.8 kg of PCM in addition to the internal reflector increased total production for vaseline by 110.68 % and 45.72 %, 124.74 % and 51.91 % for soy wax in spring and summer, respectively. Soy wax has the benefits of being both inexpensive and very productive. The distillate enhancement of solar still with various non-paraffin organic PCMs can be seen in Fig. 11. It is evident that lauric acid, beeswax, petroleum wax, and soy wax have garnered significant attention in recent studies for solar distillation application, primarily due to their widespread availability, cost-effectiveness, and lower environmental impact.

6.3.5. *Paraffin (organic PCM) with various solar stills*

Paraffin wax is the most used PCM for thermal energy storage despite low thermal conductivity. Paraffin waxes are a type of hydrocarbon with a long-structured chain (C_nH_{2n+2}), primarily consisting of alkanes. The Properties of these alkanes, which are made up of carbon and hydrogen atoms, are influenced by the molecular arrangement found within the paraffin structure, particularly in their role as PCMs. These compounds are part of the alkane family (CH_3–(CH_2)–CH_3), characterized by hydrocarbon chains that are interconnected through van der Waals forces [213,214]. These forces are relatively lower than covalent bonds, allowing the paraffin molecules to move fast and easily. The ability of paraffin wax to efficiently store energy is mainly due to its high latent heat of fusion, which is the amount of energy released or absorbed during the phase change process [52,215]. The latent heat mechanism allows paraffin wax to store substantial energy in a relatively small volume, making it an attractive choice for various thermal energy storage applications [216,217].

6.4. *Passive solar still loaded with paraffin wax*

Passive solar still serves as a crucial apparatus capable of generating increased distillate without additional alterations. Furthermore, modifications are made to the equipment to improve the overall distillate yield. Passive solar stills represent the simplest and most cost-effective choice; however, their distillate output falls significantly short compared to active solar stills. Therefore, several researchers used paraffin as PCM to boost the still's total distillate yield. A summary of a few recent research papers with comparable aims follows. For instance,

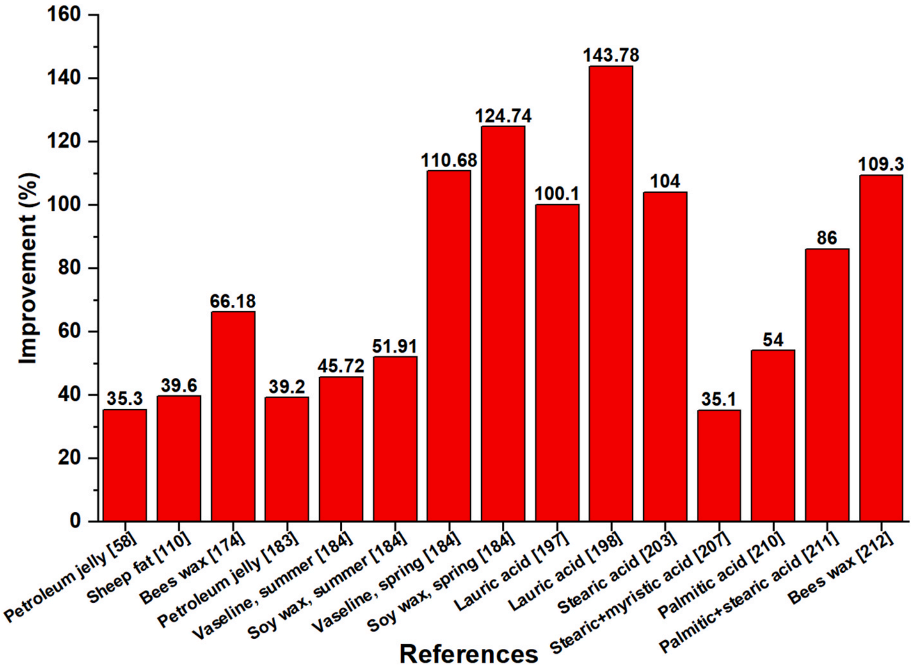


Fig. 11. Distillate yield improvement (%) with organic PCMs.

Satyamurthy et al. [218] conducted an experimental investigation on PSS; for the study, paraffin wax was used as PCM under the still basin. The experiment was carried out with and without PCM. Results show an increment of 20 % in the daily distillate of PSS with PCM compared to PSS without PCM. The paraffin wax provides extra heat to basin water without solar radiation, improving the PSS's distillate output. Satyamurthy et al. [219] carried out an experiment with similar sight on TPSS for the climatic condition of Chennai. The experiment setup was loaded with paraffin wax for the study. The finding revealed a 35 % improvement in the overall daily distillate of modified TPSS compared to normal TPSS. Also, the absorber plate temperature seemed approximately equal to the basin temperature for the morning hour. Furthermore, the paraffin temperature remains constant during the mid-noon due to latent heat transfer. Shalaby et al. [220] investigated the effect of paraffin wax and wick on SBSS, as shown in Fig. 12a. The basin of the still was made of copper and had a v-corrugated shape. The results showed that the still loaded with 25 kg of paraffin wax and wick had better distillate output than 35 kg due to better climatic conditions. The results also revealed that the day productivity of the still was low compared to CSS. In contrast, night productivity was increased due to the heat stored and capillary action provided by the wick, which decreased the evaporation time of the MSS. The overall yield obtained by the system can be seen in Fig. 12b.

In a similar study, the SSSS was modified with three different PCMs (lauric acid, stearic acid, and paraffin wax) filled in six copper cylinders with 1.3 kg PCM each for all the cases. The experiment was conducted at five different water depths, 1–5 cm. The finding revealed that the paraffin wax shows better distillate output by 8.14 % and 12.3 % compared to stearic and lauric acid due to high latent heat storage capacity at lower water depth. Furthermore, cylindrical containers for PCMs increase surface area and produce more distillate output than spherical-shaped containers [221]. Moreover, a similar study was performed to improve the distillate output of the CSS. The CSS was modified with square hollow fins attached to the basin liner and paraffin wax as PCM. Results revealed that including fins and paraffin wax is a heat storage material and increases daily productivity by 95 % compared to CSS. Also, the productivity of the MSS was approximately doubled at night compared to CSS due to extra attachments provided to the still [222]. Moreover, Kabeel et al. [223] investigated the effect of paraffin wax and hollow circular fins on PSS's cumulative daily distillate yield, as shown in Fig. 13a. It was revealed that the productivity of the MSS increased by 101.5 % compared to CSS, as shown in Fig. 13b. In addition, it has also seemed that the PCM decreases the losses from the bottom and sides and acts as a heat storage medium, thus helping to augment cumulative yield.

Jahanpanh et al. [224] used 3 kg and 6 kg of PCM28/315 to increase the daily distillate productivity of the SSSS. The used PCM28/315 consists of inorganic salt hydrates, water, and additives. The PCM-loaded pouch was placed beneath the stainless-steel material basin. The PCM seems to undergo only one cycle of melting and solidification daily. The PCM melts after 1:00 pm and solidifies after 6:00 pm as the water temperature decreases. Moreover, the results revealed that productivity also depends on the quantity of the PCM used up to a specific limit. Also, an augmentation of 30.3 % in productivity was found for SSSS with 6 kg of PCM compared to reference solar still. Mohammed et al. [225] used three different quantities (2 kg, 4 kg, and 6 kg) of PCM (RT-42) beneath the basin of the SSSS. The maximum distillate was found for 4 kg of PCM due to increased water temperature compared to 6 kg of PCM. Moreover, as the amount of PCM increases, the basin water temperature during daytime decreases as the heat from basin water is transferred and stored by PCM. The results revealed a 39.9 % increment in overall daily productivity of the MSS with 4 kg of PCM compared to the conventional

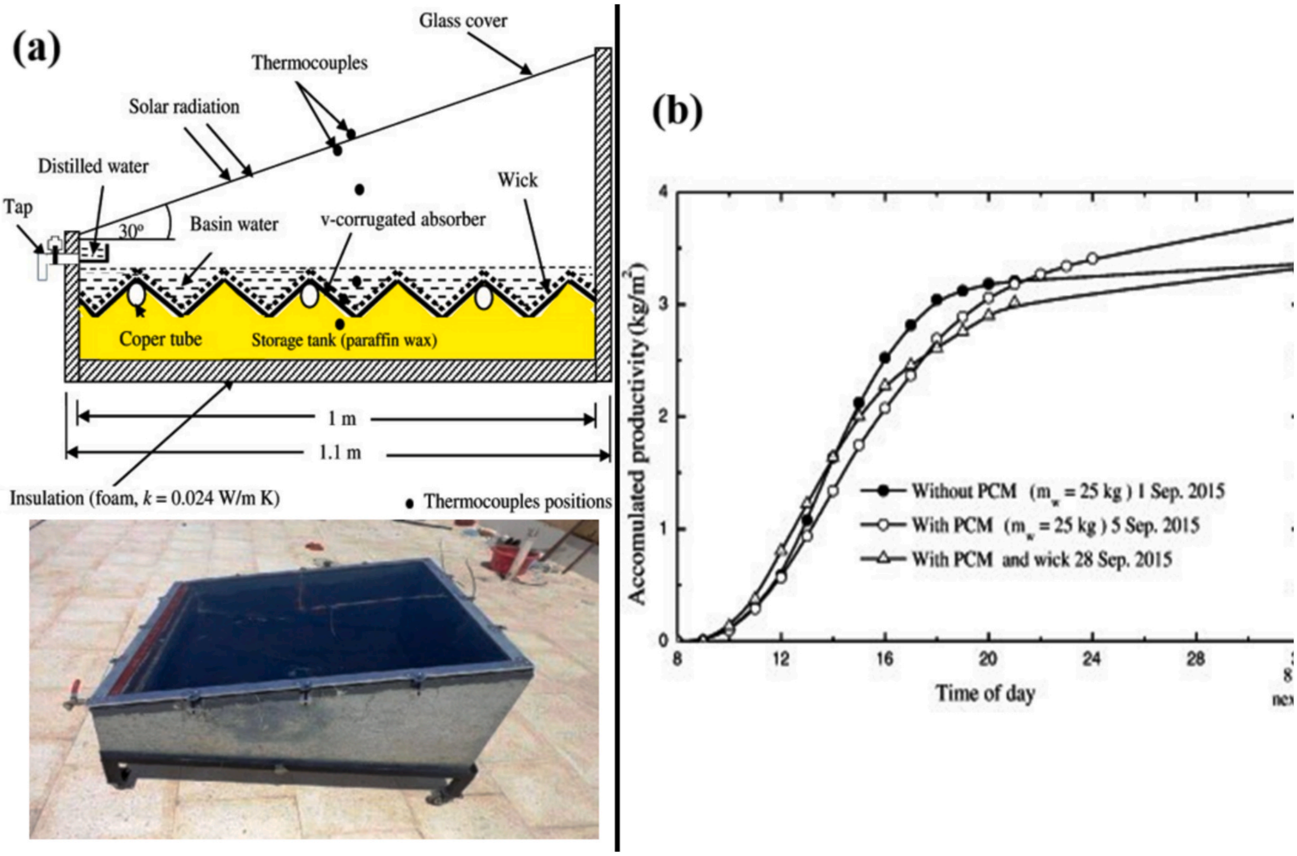


Fig. 12. (a) Schematic layout and photographic view of the paraffin wax incorporated solar still (b) Accumulated productivity [220]. (Adopted with permission, License number: 5970450372904).

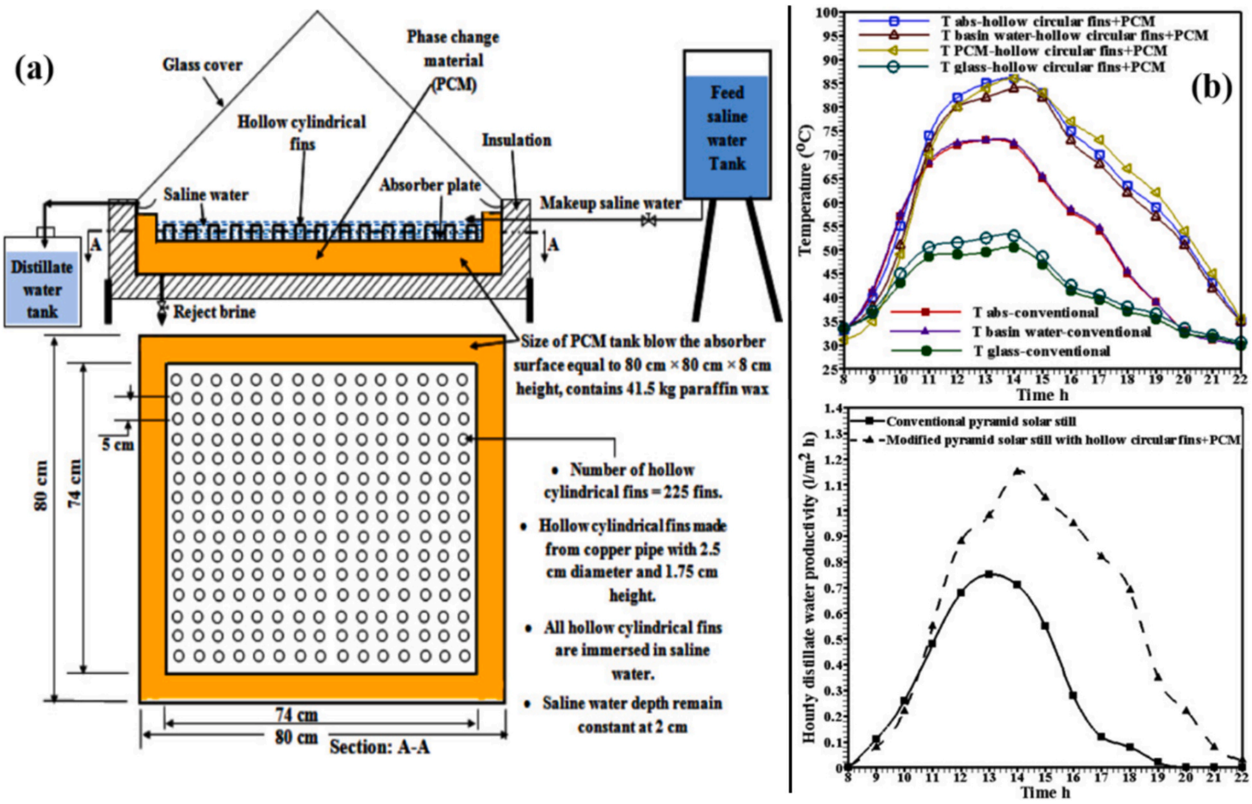


Fig. 13. (a) Schematic representation of the MSS, (b) Temperature and hourly yield variation of the MSS [223]. (Adopted with permission, License number: 5970451126013).

one. Radomska et al. [226] validated a theoretical study on the variation of paraffin (PCM) mass with the help of an experimental study. The results revealed that the maximum basin water temperature decreases as PCM increases. Still, it remained high longer than the lesser amount of PCM. Moreover, the distillate yield was increased by 47.1 % when the PCM was heated outside and placed into the still as the basin water temperature decreased. Distillate improvement of various passive solar stills with paraffin wax as a PCM is shown in Fig. 14.

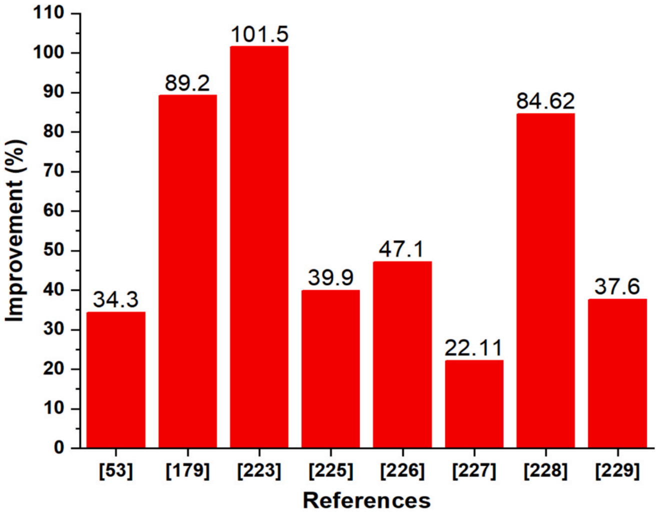


Fig. 14. Distillate yield improvement (%) of passive solar still with paraffin wax PCMs [53,179,223,225–229].

6.5. *Active solar still loaded with paraffin wax*

In active solar stills, the external attachments are integrated into the passive system to increase the system's overall performance in distillate yield. These attachments include condensers, collectors, fins, water heaters, heat exchangers, etc. [268]. Tuly et al. [230] used fins, an external condenser, a black cotton cloth (wick), and paraffin (PCM) in DSSS. The results show a 24.7 % improvement in accumulated yield compared to the reference still. It has been reported that if the basin temperature goes below PCM temperature, the PCM transfers its latent heat to basin water, and fins increase heat transfer from PCM to the basin [230]. Another experiment was performed by integrating FPC and paraffin wax to solar still for three different water depths (1 cm, 2 cm, and 3 cm). It has been deemed from the observations that FPC preheats the incoming basin water, and paraffin wax increases basin water temperature during off-sunshine hours. The results revealed that the simultaneous use of FPC and paraffin wax can improve the productivity and efficiency of solar still [231]. Aly et al. [232] used paraffin wax and water sprinkler to augment the distillate output of the investigated solar still. The experiments were performed by varying basin water depth by 0.5 cm to 2 cm. The basin water temperature reached about 70 °C with PCM, which was 7.14 % higher than without PCM. The study's results disclosed a 32.48 % increment in cumulative yield of solar still with PCM and water sprinkler compared to conventional one. A similar improvement of 48 % and 54 % was noted with solar concentrated still and solar still coupled to the parabolic dish and paraffin wax [233,234]. Furthermore, the double-pass solar air collector was connected to a paraffin wax-enriched solar still. The study shows a 108 % improvement in distillate yield compared to conventional one [235]. Chaichan et al. [236] reported a 783 % improvement in distillate yield by integrating conical solar still with a concentrating unit and paraffin wax. Zarei et al. [269] examines the effects of incorporating modified solar water preheater, paraffin PCM, and copper fins into a zigzag cascade solar still.

The modified solar stills incorporating solar water preheaters, PCM, and fins achieved a peak thermal efficiency of 42.65 %. The summary of the distillate yield improvement (%) of active solar still is represented in Fig. 15.

The above section includes a deep literature review on passive and active solar stills with and without PCM. Based on the theoretical study, it was learned that the distillate yield of passive solar still fluctuates in some cases with and without PCM compared to active solar stills. The design of solar stills and many more operational and climatic factors can be considered significant parameters for influencing the productivity of the solar still and enhancement in distillate output in reference solar still compared to the modified one. However, from the literature review, it has also seemed that organic PCMs like paraffin have shallow thermal properties compared to salt hydrates, which were observed to be deciding factors in selecting the best PCM for solar still. Furthermore, there is a broad scope in increasing paraffin wax's thermal and physical properties by adding various micro and nanoparticles.

6.6. Economic analysis of PCMs incorporated solar still

Economic analysis is the most important criterion to evaluate when considering a system. To do so, cost per liter of distilled water (CDW) is assessed by considering the various costs such as fabrication, operating, salvage value, and maintenance. Here the cost of PCM is quite important as it significantly affects the CDW obtained during operating period. Therefore, various theoretical calculations such as capital recovery factor (CRF), sinking fund factor (SFF), fixed annual cost (FAC), annual salvage value (ASV), annual cost (AC), cost per liter of distilled water (CDW), and net payback period (PBP) are considered to check the economic feasibility of the PCM incorporated solar distillation system. All the factors related to economic analysis calculated using following equations [243].

$$CRF = \frac{i_r(i_r+1)^n}{(i_r+1)^n-1} \tag{5}$$

Where, n = number of years and i_r = interest rate.

$$FAC = CRF \times systeminitialcost \tag{6}$$

$$SFF = \frac{i_r}{(i_r+1)^n-1} \tag{7}$$

$$ASV = SFF \times 0.2 \times SC_{initial} \tag{8}$$

Where$SC_{initial}$ = system initial cost.

$$AC = 1.15FAC - ASV \tag{9}$$

Where; FAC= fixed annual cost.

$$CDW = \frac{AC}{AY} \tag{10}$$

Where; AY= Annual yield of solar still.

$$PBP = \frac{ln\left[\frac{AY \times Sellingprice}{AY \times Sellingprice - (SC_{initial} - i_r)}\right]}{ln(1+i_r)} \tag{11}$$

Generally the cost of PCM varied based on their utility. For instance, the cost of raw PCM will be much lower compared to refined PCM. However, the properties of refined PCM will be much higher compared to a raw PCM. The cost of PCM i.e., used for solar distillation ranges from 1.2 to 8.2 $/kg as per their utility. The cost of myristic acid, paraffin wax and organic natural PCM is quite low compared to other PCMs especially (A) series making it more economical. Therefore, cost and thermal properties should be balanced out to check the performance of the solar still. For instance, Nian et al. [244] performed experimental and simulation studies over the active and passive solar still with and without PCM (paraffin wax). Fig. 16a and b show the schematic diagram and pictorial view of the solar stills. The experiments were carried out for three cases viz: (1) CSS, (2) CSS with shape-stabilized PCM, and (3) CSS with shape-stabilized PCM and solar collectors. The studies were later compared for best distillate yield output and economic analysis. The solar stills' total annual cost and pay-back period can be seen in Fig. 16c and Fig. 16d.

It was reported that the PCM-based conventional solar still was efficient in terms of "TAC," which was reported at 0.017 **$**/liter, while the highest obtained for only CSS was 0.019 **$**/liter. The thermal conductivity of the PCM material is an important parameter that affects the cost per liter of water. An experiment was performed with similar sight

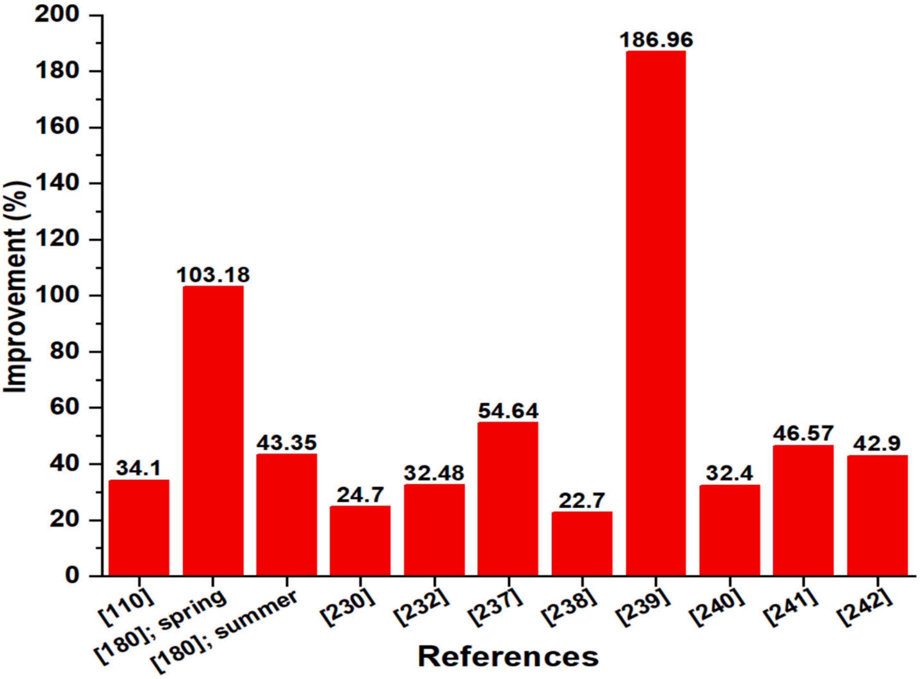


Fig. 15. Distillate yield improvement (%) of active solar still with paraffin wax PCMs [110,180,230,232,237–242].

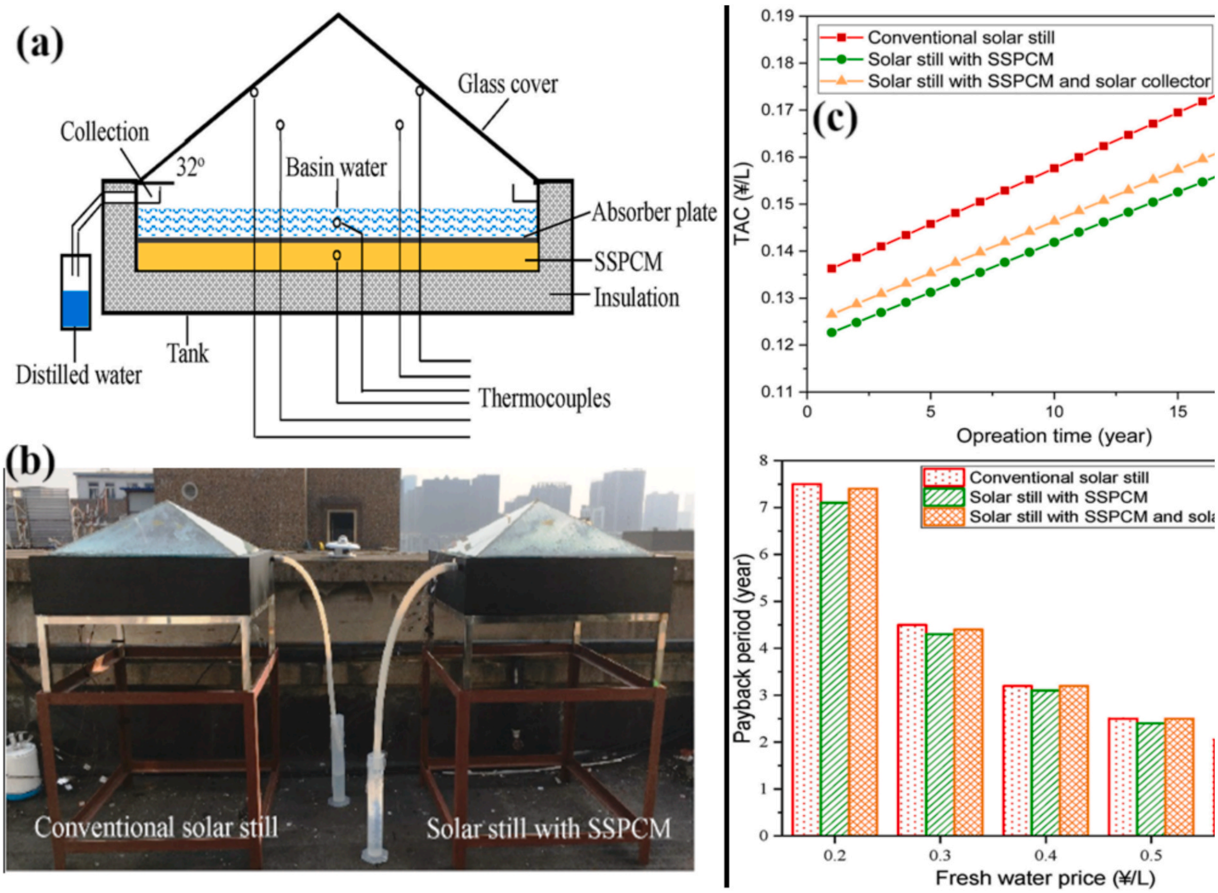


Fig. 16. (a) Schematic Diagram of CSS (b) Pictorial view of working solar stills (c) Total annual cost of operating solar stills (d) Pay Back Period of operating solar stills [244]. (Adopted with permission, License number: 5970451312638).

to obtain clear vision. The author used two different materials (galvanized iron and acrylic) for the basin surface with and without PCM. The results were compared to conventional solar still with no modification. The cost obtained per liter of distilled water was found to be economical. However, the cost of modification increases the cost of obtaining water. For CSS, GI + PCMSS, and ABSS + PCMSS, the price of the obtained liter was found to be 0.67, 1.09, and 0.015 **$**/liter, respectively [245]. The list of summaries of the economic analysis is tabulated in Table 3.

6.7. *Energy matrices of PCM embedded solar still*

6.7.1. *Exergo-economic analysis*

The system's viability cannot be assessed without exergy analysis. Exergy is directly related to the economy of the system. The higher the exergy, the higher the systems running cost. The exergo-economic analysis approach includes analyzing helpful work and its respective incurred cost, based on the principles of energy and exergy. This method involves an annual evaluation of energy, using Eq. (12) and (13), ensuring that the annual cost (AC) remains constant to optimize system performance. The primary goal is to assess the costs associated with achieving optimal values and to develop cost-effective systems. This approach aids technologists in identifying alternative solutions for improving the overall cost efficiency of devices. These parameters can be evaluated based on energy and exergy, as represented in equations (5) and (6). In a recent study, Yousef et al. [255] modified CSS separately with PCM (seen in Fig. 17a), PCM + pin fin (PF), steel wool fiber + PCM, and steel wool fiber alone. The variation in energy and exergy output for the respected cases has been shown in Fig. 17b and Fig. 17c respectively. It was observed that the monthly exergy output was increased by 9.4 %, 7.4 %, and 4.6 % for the solar still employed with PCM + SWF, followed by PCM + PF and PCM alone, respectively.

$$\varnothing_{energy} = \frac{E_{energy-out-annual}}{AC} \tag{12}$$

$$\varnothing_{exergy} = \frac{E_{exergy-out-annual}}{AC} \tag{13}$$

6.7.2. *Enviro-economic analysis*

The environmental effect caused during the system's operation is estimated as CO_2 emission. The cost analysis related to CO_2 emissions is conducted to promote the adoption of non-conventional energy sources, such as renewable energy systems, within existing frameworks. The aim is to increase the maximum utilization of carbon-free energy. It has been reported that the release of CO_2 into the environment is approximately 0.96 kg/kWh. However, accounting for transmission losses (20 %) and distribution losses (40 %), the actual CO_2 emission rises about 2 kg/kWh. The mitigation of CO_2 emissions per year can be calculated using equations (14) and (15), which are based on energy and exergy principles. Abdel-Aziz et al. [241] modified a CSS with paraffin wax and an electric heater to improve the system's overall efficacy. The temperature of the heater was varied from 58 °C to 65 °C. Exergo-economic and enviro-economic studies were conducted to check the feasibility of the system. It was observed that integrating paraffin wax and heater operating at 65 °C can mitigate 166.4 tons of CO_2 during the life span, which was reported to be 479.38 % higher than CSS. The list of the previously published literature focusing on exergoconomic and enviroeconomic analysis is tabulated in Table 4.

$$\varphi_{CO2} = \frac{E_{energy-out-annual}}{10^3} \times \frac{\varphi_{CO2}}{0.38} \tag{14}$$

Table 3
Cost of obtained distillate yield along with PBP for various solar stills.

Reference	Solar still type	Solar still design	PCM	Modification	Distillate yield (ml/m^2.day)	CDW ($)	PBP (days)
	Paraffin based passive solar still						
[50]	Passive	SSSS	RT50	PCM + silver particles + plant extract	8106	0.014	–
[56]	Passive	SSSS	A48	PCM + Conventional still	6500	0.014	~132
[57]	Passive	SSSS	A48	PCM + natural fiber	–	0.018	~106
[183]	passive	SSSS	Paraffin wax	PCM + aluminium nanoparticles	342	0.0107	–
[183]	passive	SSSS	Paraffin wax	PCM + scrap aluminium	304	0.0115	–
[184]	Passive	SSSS	Paraffin wax	Internal reflector	4950	0.044	–
[221]	Passive	SSSS	Paraffin wax	PCM filled in copper cylinder	1202	–	–
[247]	Passive	SSSS	Paraffin wax	Composite bed	3270	0.0019	–
[252]	Passive	CSS	Paraffin wax	PCM + sand + soil	–	~0.027	~56
[253]	Passive	Single basin semi-cylindrical still	Paraffin wax	PCM + 1 cm, basin water depth	3860	0.0145	112
[253]	Passive	Single basin semi-cylindrical still	Paraffin wax	PCM + 2 cm, basin water depth	3556	0.0159	125
[253]	Passive	Single basin semi-cylindrical still	Paraffin wax	PCM + 3 cm, basin water depth	3172	0.0183	145
[253]	Passive	Stepped basin semi-cylindrical still	Paraffin wax	PCM + 1 cm, basin water depth	4251	0.0132	103
[253]	Passive	Stepped basin semi-cylindrical still	Paraffin wax	PCM + 2 cm, basin water depth	3889	0.0157	123
[253]	Passive	Stepped basin semi-cylindrical still	Paraffin wax	PCM + 3 cm, basin water depth	3345	0.0181	143
[275]	Passive	SSSS	Paraffin wax	Corrugated absorber	4500	0.0035	–
[280]	Passive	HSS	Paraffin wax	PCM filled in 4 soda cans	4880	0.0111	–
[280]	Passive	HSS	Paraffin wax	PCM filled in 3 soda cans	5630	0.0128	–
[284]	Passive	SSSS	$MgCl_2\cdot 6H_2O$	PCM + potassium chloride + parabolic collector + nanoparticles	3261	0.012	129
[284]	Passive	SSSS	Paraffin wax	PCM + potassium chloride + parabolic collector + nanoparticles	~2682	0.014	156
	Non-paraffin based passive solar still						
[56]	Passive	SSSS	Stearic acid	PCM + Conventional still	~5571	0.015	~146
[56]	Passive	SSSS	Capric + palmitic	PCM + Conventional still	~6800	0.0125	~120
[56]	Passive	SSSS	$CaCl_2\cdot 6H_2O$	PCM + Conventional still	~2788	0.0225	200
[58]	Passive	SSSS	Petroleum jelly	PCM	2958	0.037	205
[184]	Passive	SSSS	Vaseline	Internal reflector	5100	0.044	–
[184]	Passive	SSSS	Soy wax	Internal reflector	5400	0.0419	–
[207]	Passive	DSSS	Myristic + stearic	PCM	2440	0.014	–
[207]	Passive	DSSS	Myristic + stearic	PCM + steel wool fiber	3400	0.013	–
[209]	Passive	CSS	Palmitic acid	PCM	4900	0.019	97
[221]	Passive	SSSS	Stearic acid	PCM filled in copper cylinder	1015	–	–
[221]	Passive	SSSS	Lauric acid	PCM filled in copper cylinder	930	–	–
[248]	Passive	CSS	Stearic acid	Wax filled rods	3195	0.014	–
[254]	Passive	SSSS	SP42	2.5 kg PCM in autumn	1715	0.075	–
[254]	Passive	SSSS	SP42	3 kg PCM in summer	3195	0.040	–
[289]	Passive	SSSS	Petroleum jelly	PCM in copper cylinder	2945	0.038	–
[289]	Passive	SSSS	Petroleum jelly	PCM + nanoparticles in copper cylinder	4075	0.031	–
	Non-paraffin based active solar still						
[195]	Active	SSSS	Palmitic acid	PCM + pin fin	–	0.018	81
[195]	Active	SSSS	Lauric acid	PCM + pin fin	–	0.02	87
[195]	Active	SSSS	Stearic acid	PCM + pin fin	–	0.016	72
[198]	Active	PSS	Lauric acid	PCM + fin	6071	0.014	123
[198]	Active	PSS	Lauric acid	PCM + fin + fogger	4451	0.010	94
[174]	Active	TSS	Bees wax	Heat exchanger + PCM	8060	–	–
[203]	Active	SSS	Stearic acid	PCM	910	–	–
[203]	Active	SSS	Stearic acid	PCM + condenser	1300	–	–
[209]	Active	CSS	Palmitic acid	PCM + pin fin	5400	0.0176	89
[276]	Active	SSSS	$Na_2S_2O_3\cdot 5H_2O$	Solar collector + PCM + double glass cover + heat exchanger + glass cover cooling	4300	–	–
[278]	Active	SSSS	–	PCM + heating coil + condenser + nano silver	6550	0.024	–
[298]	Active	Traditional solar still	Stearic acid	PCM	2200	0.033	–
[298]	Active	Traditional solar still	Stearic acid	PCM + evacuated solar collector	6270	0.036	–
	Paraffin based active solar still						
[229]	Active	Modified solar still	Paraffin wax	PCM + pulsating heat pipes + condenser	6793	0.0093	–
[242]	Active	SSSS	Paraffin wax	Thermosyphon heat pipe + 0.9 m PCM	–	0.0469	–
[242]	Active	SSSS	Paraffin wax	Thermosyphon heat pipe + 1.8 m PCM	–	0.0456	–
[242]	Active	SSSS	Paraffin wax	Pulsating heat pipe + 0.9 m PCM	–	0.0483	–
[242]	Active	SSSS	Paraffin wax	Pulsating heat pipe + 1.8 m PCM	–	0.0458	–
[246]	Active	SSSS	Paraffin wax	Hollow fin absorber	4085	0.032	192
[246]	Active	SSSS	Paraffin wax	Solid fin absorber	3485	0.034	207

(*continued on next page*)

Table 3 (*continued*)

Reference	Solar still type	Solar still design	PCM	Modification	Distillate yield (ml/m^2.day)	CDW ($)	PBP (days)
[249]	Active	PSS	Paraffin wax	PCM + fin	3440	0.031	169
[249]	Active	PSS	Paraffin wax	PCM + fin + gravels	4800	0.020	124
[250]	Active	Trays solar still	Paraffin wax	PCM + reflectors + heating coils	8450	0.021	98
[251]	Active	DSSS	Paraffin wax	PCM + fin + transmission oil	3780	0.022	~158
[269]	Active	zigzag cascade solar still	Paraffin wax	PCM + solar water preheater + fin	3806	0.0617	–
[270]	Active	Modified DSSS	Paraffin wax	PCM	1510	0.0204	283
[270]	Active	Modified DSSS	Paraffin wax	PCM + nanomaterial	1835	0.0199	258
[277]	Active	TSS	Paraffin wax	Heat exchanger + PCM + convex absorber + black jute wick	13,580	0.0056	–
[279]	Active	PSS	Paraffin wax	PCM	3330	0.030	175
[279]	Active	PSS	Paraffin wax	PCM + black cotton cloth	3690	0.027	160
[279]	Active	PSS	Paraffin wax	PCM + black cotton cloth + jute cloth	3370	0.030	174
[281]	Active	CSS	Paraffin wax	PCM + parabolic trough collector	6150	0.050	–
[282]	Active	TSS	Paraffin wax	PCM tubes + parabolic solar concentrator	5550	0.00782	–
[283]	Active	CSS	Paraffin wax	PCM + heating coils	~6849	0.017	–
[285]	Active	TSS	Paraffin wax	PCM + parabolic solar concentrator + nanoparticles coated rotating cylinder	9540	0.024	180
[286]	Active	PSS	Paraffin wax	PCM + turbulator + nano-paint + thermoelectric cooling module	604	0.023	–
[286]	Active	PSS	Paraffin wax	PCM + turbulator + nano-paint + thermoelectric heating module	1080	0.0127	–
[287]	Active	CSS	Paraffin wax	PCM + fins + nanoparticles + crushed stone	2400	0.0228	135
[287]	Active	CSS	Paraffin wax	PCM + fins + nanoparticles + black sand	3200	0.0192	126
[288]	Active	Corrugated drum solar still	Paraffin wax	PCM + nanoparticles	7600	0.039	–
[297]	Active	SSSS	Paraffin wax	PCM + finned absorber + nanoparticles	–	0.014	~137

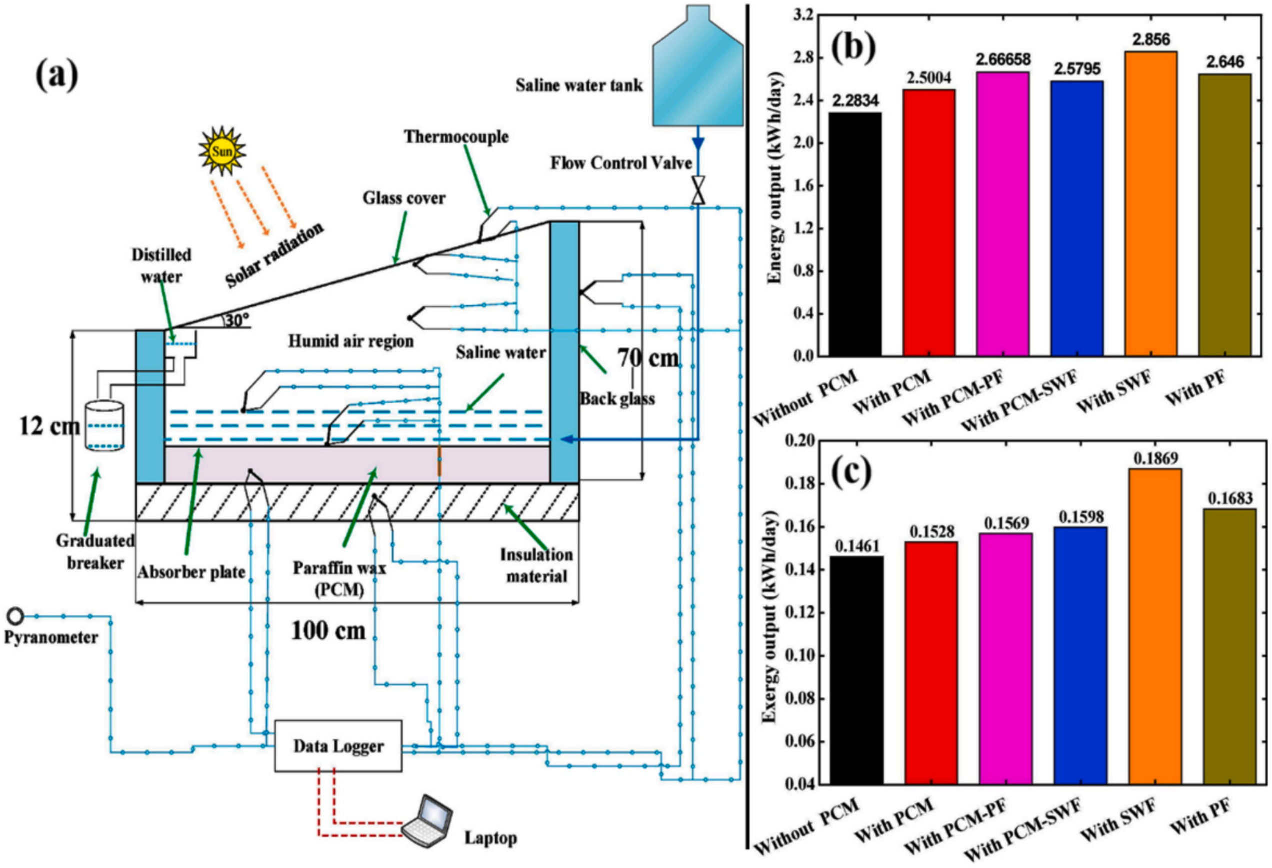


Fig. 17. (a) Layout of the solar still (b) Variation in energy output (c) Variation in exergy output [255] (Adopted with permission, License number: 5970451501762).

$$\varphi_{CO2} = \frac{E_{exergy-out-annual}}{10^3} \times \varphi_{CO2} \tag{15}$$

Based on the previous studies, CO$_2$ mitigation within a year and during the complete life span has been provided for better knowledge. Table 4 compares energy-economic parameters based on energy and exergy on various solar stills, including several modifications. Additionally, the total CO$_2$ mitigated during the operation period of the particular

Table 4
Highlights the recently published articles on energo-economic and exergo-economic analysis and total CO_2 mitigated during the operational period.

Author/Ref.	Application	Modification	Location	Energo-economic (Energy) kWh/$	Exergo-economic (Exergy) kWh/$	Total CO_2 mitigation/year (Tonnes)	Total CO_2 mitigation during life span (Tonnes)
Abdel-Aziz et al. [241]	Water purification	CSS	Egypt	–	–	1.414	28.28
Abdel-Aziz et al. [241]	Water purification	CSS + PCM	Egypt	–	–	4.33	86.615
Abdel-Aziz et al. [241]	Water purification	CSS + PCM + electric heater (58 °C)	Egypt	–	–	4.39	87.84
Abdel-Aziz et al. [241]	Water purification	CSS + PCM + electric heater (60 °C)	Egypt	–	–	5.24	104.87
Abdel-Aziz et al. [241]	Water purification	CSS + PCM + electric heater (65 °C)	Egypt	–	–	7.9895	159.79
Hemmatian et al. [242]	Water purification	Thermosyphon heat pipe + 0.9 m PCM	Iran	28.22	1.64	–	~18.20
Hemmatian et al. [242]	Water purification	Thermosyphon heat pipe + 1.8 m PCM	Iran	29.99	1.75	–	~19
Hemmatian et al. [242]	Water purification	Pulsating heat pipe + 0.9 m PCM	Iran	28.30	1.65	–	~18.15
Hemmatian et al. [242]	Water purification	Pulsating heat pipe + 1.8 m PCM	Iran	30.76	1.79	–	19.53
Mahala and Sharma [249]	Water purification	PSS + PCM + fin	India	–	–	–	13.89
Mahala and Sharma [249]	Water purification	PSS + PCM + fin + gravels	India	–	–	–	19.14
Alqsair [250]	Water purification	Trays solar still + paraffin wax + nanoparticles	Saudi Arabia	–	–	34.2	684
Mustafa et al. [254]	Water purification	SSSS + 1 kg PCM	Egypt	–	–	–	5.12
Mustafa et al. [254]	Water purification	SSSS + 1.5 kg PCM	Egypt	–	–	–	6.51
Mustafa et al. [254]	Water purification	SSSS + 2 kg PCM	Egypt	–	–	–	8.42
Yousef et al. [255]	Water purification	CSS	Egypt	2.2834	0.1461	33.02	990.6
Yousef et al. [255]	Water purification	CSS + PCM	Egypt	2.5004	0.1528	35.88	1076.4
Yousef et al. [255]	Water purification	CSS + PCM + Pin fin	Egypt	2.66658	0.1569	38.26	1147.8
Yousef et al. [255]	Water purification	CSS + PCM + Steel wool fiber	Egypt	2.5795	0.1598	37.05	1111.5
Yousef et al. [255]	Water purification	CSS + steel wool fiber	Egypt	2.856	0.1869	41.6	1248
Yousef et al. [255]	Water purification	CSS + pin fin	Egypt	2.646	0.1683	38.35	1150.5
Yousef et al. [256]	Water purification	PCM	Egypt	–	8.5	1.06	28.83
Hassan et al. [257]	Water purification	MSS + PTC	Egypt	–	4.95	3.87	38.73
Hassan et al. [257]	Water purification	MSS + Porous media	Egypt	–	3.87	2.27	22.77
Hassan et al. [257]	Water purification	MSS + sand inside the basin + PTC	Egypt	–	5.92	4.4	44.01
Elfadl et al. [258]	Water purification	Corrugated aluminium sheet heat sink condenser	Egypt	4.309	–	1.69	15.83
Elfadl et al. [258]	Water purification	Corrugated aluminium sheet heat sink condenser + vertical rectangular fins	Egypt	3.93	–	1.57	14.7
Elfadl et al. [258]	Water purification	Aluminium sheet heat sink condenser + pin fins	Egypt	4.369	–	1.82	17.15
Elfadl et al. [258]	Water purification	Aluminium sheet heat sink condenser + pin fins	Egypt	2.865	–	1.49	13.68
Piyush et al. [259]	Water purification	Jute wick	India	–	2.35	7.97	385.8
Piyush et al. [259]	Water purification	Black cotton wick	India	–	2.97	7.37	355.85
Sahota et al. [260]	Water purification	Aluminium oxide nanoparticles	India	–	0.74	7.72	376.2
Sahota et al. [260]	Water purification	Titanium dioxide nanoparticles	India	–	0.57	7.26	353.26
Sahota et al. [260]	Water purification	Copper oxide nanoparticles	India	–	0.39	6.86	333.24
Sahota et al. [260]	Water purification	CSS	India	–	3.07	6.07	293.9

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Table 4 (*continued*)

Author/Ref.	Application	Modification	Location	Energo-economic (Energy) kWh/$	Exergo-economic (Exergy) kWh/$	Total CO_2 mitigation/year (Tonnes)	Total CO_2 mitigation during life span (Tonnes)
Rastegar et al. [261]	Water purification	CSS	Iran	–	0.32	3.76	75.2
Rastegar et al. [261]	Water purification	CSS + heat pipe heat exchanger	Iran	–	0.25	7.74	154.8
Shatar et al. [262]	Water purification	CSS + partially coated condensing cover + thermoelectric cooling capacity	Malaysia	4.64	1.33	2.97	74.25
Tuly et al. [270]	Water purification	Modified DSSS + PCM	Bangladesh	28.37	2.16	–	3.04
Tuly et al. [270]	Water purification	Modified DSSS + PCM + nanomaterial	Bangladesh	30.07	2.57	–	3.65
Attia et al. [271]	Water purification	HSS + three cylindrical magnets	Algeria	11.37	0.50	–	3.49
Attia et al. [271]	Water purification	HSS + four cylindrical magnets	Algeria	11.90	0.62	–	3.93
Aftiss et al. [272]	Water purification	CSS + static PCM	Morocco	730.06	63.17	–	21.44
Aftiss et al. [272]	Water purification	CSS + dynamic PCM	Morocco	878.46	87.30	–	27.4
Abdel-Aziz and Attia [273]	Water purification	CSS + white transparent broken glass	Algeria	37.341	2.851	–	1.7331
Abdel-Aziz and Attia [273]	Water purification	CSS + blue broken glass	Algeria	39.448	3.281	–	1.8436
Abdel-Aziz and Attia [273]	Water purification	CSS + brown broken glass	Algeria	43.919	4.396	–	2.078
Abdel-Aziz and Attia [273]	Water purification	CSS + green broken glass	Algeria	41.558	3.575	–	1.954
Mahala and Sharma [279]	Water purification	Paraffin wax	India	–	–	0.651	9.76
Mahala and Sharma [279]	Water purification	Paraffin wax + black cotton cloth	India	–	–	0.731	10.97
Mahala and Sharma [279]	Water purification	Paraffin wax + black cotton cloth + jute cloth	India	–	–	0.669	10.03
Kannan et al. [280]	Water purification	HSS with paraffin wax in aluminium 4 soda cans	India	–	–	1.54	15.4
Kannan et al. [280]	Water purification	HSS with paraffin wax in aluminium 3 soda cans	India	–	–	1.34	13.4
Parsa et al. [286]	Water purification	Paraffin wax + turbulator + nano-paint + thermoelectric cooling module	Iran	–	–	~0.77	9.237
Parsa et al. [286]	Water purification	Paraffin wax + turbulator + nano-paint + thermoelectric heating module	Iran	–	–	1.671	20.052
Saeed et al. [287]	Water purification	Corrugated drum solar still Paraffin wax + nanoparticles	Egypt	–	–	–	14
Anika et al. [288]	Water purification	Paraffin wax + fins + nanoparticles + crushed stone	Bangladesh	–	7.375	0.4952	–
Anika et al. [288]	Water purification	Paraffin wax + fins + nanoparticles + black sand	Bangladesh	–	7.3865	0.565	–
Pandey and Naresh [290]	Water purification	Conventional PSS	India	–	3.43	~0.92	13.75
Pandey and Naresh [290]	Water purification	Modified PSS with pulsating heat pipe	India	–	4.06	~1.253	18.79
Attia et al. [291]	Water purification	HSS + copper tubes	Algeria	14.88	0.70	0.26	3.85
Attia et al. [291]	Water purification	HSS + copper tubes + nanoparticles	Algeria	17.12	0.91	0.32	4.76
Elbar et al. [292]	Water purification	CSS	Egypt	43.3243	2.5753	19.38	387.6
Elbar et al. [292]	Water purification	CSS + PV panel + DC heater + DC Battary	Egypt	45.3848	2.008	35.832	716.64
Suraparaju et al. [293]	Water purification	SSSS	India	–	–	0.704	7.04
Suraparaju et al. [293]	Water purification	SSSS + engine oil + paraffin wax	India	–	–	0.1132	11.32
Mankai et al. [294]	Water purification	CSS + hollow bricks	Tunisia	–	–	–	94.26
Elamy et al. [295]	Water purification	cylindrical still + paraffin wax + nanoparticles + absorber + parabolic solar concentrator + condenser	Egypt	–	–	30.8	616
Subramanian et al. [296]	Water purification	SSSS + paraffin wax	India	–	–	0.554	11.08

(*continued on next page*)

Table 4 (*continued*)

Author/Ref.	Application	Modification	Location	Energo-economic (Energy) kWh/$	Exergo-economic (Exergy) kWh/$	Total CO_2 mitigation/year (Tonnes)	Total CO_2 mitigation during life span (Tonnes)
Subramanian et al. [296]	Water purification	SSSS + paraffin wax + nano coated copper pipes	India	–	–	0.571	11.42
Subramanian et al. [296]	Water purification	SSSS + paraffin wax + nano coated copper pipes + copper oxide nanoparticles	India	–	–	~0.70	13.91
Subramanian et al. [296]	Water purification	SSSS + paraffin wax + nano coated copper pipes + aluminium nitride nanoparticles	India	–	–	0.67	13.41

desalination system within a year and its life span are also mentioned. The CSS modified with PCM can mitigate 1076.4 tons of CO_2 during its complete operating life span of 30 years [255].

7. Importance of parameters in PCM selection

The consideration of various thermophysical, chemical, and economic properties for the selection of optimal PCM is highly critical before subjecting it to heat transfer applications [299,300]. Properties that require essential examination include high latent heat, high specific heat, high density, high thermal conductivity, the melting point within the intended operating temperature range, non-flammability, non-toxicity, compatibility with container materials, no sub-cooling, ease of availability and low cost [300,301]. Organic PCMs, such as paraffin wax and fatty acids, have significant potential for thermal energy storage applications due to their high latent heat capacity, low sub-cooling, low cost, and chemical stability [301,302]. Organic PCM reportedly demonstrates low thermal conductivity, a crucial attribute for enhancing heat transfer. Hybrid PCMs are developed to resolve this issue by incorporating high-conductivity nanoparticles or employing composite structures, substantially enhancing thermal conductivity [137,303]. Several findings have been reported regarding thermal conductivity enhancement using composite PCMs. For instance, Leong et al. [304] incorporated 0.06 wt% multi-wall carbon nanotubes into paraffin wax and observed a 48 % enhancement in thermal conductivity. A 41.56 % improvement in thermal conductivity has been shown in paraffin wax when using a 2 % mass fraction of aluminium oxide and zinc oxide nanoparticles by Kibria et al. [305]. Yan et al. [306] developed copper oxide and titanium dioxide nanoparticles filled palmitic acid/stearic acid/boron nitride composites PCM and reported that thermal conductivity increased by 1.249 and 1.769 times. Gür et al. [63] reported that including Yttrium oxide nanoparticles in myristic acid led to improvements of 43.125 % in thermal conductivity and 7 % in specific heat capacity of the final nanocomposite PCM. Contrary to increased thermal conductivity and specific heat capacity of nanoparticles embedded in organic PCM, other essential properties, such as latent heat, are reported to decrease. For instance, Yu et al. [307] reported a 33.765 % increase in the thermal conductivity of lauric acid with a 6.86 % loading of copper oxide nanoparticles with a 17.57 % decrease in melting enthalpy. Including 0.15 % of silica and 0.2 % of copper oxide nanoparticles also increased the thermal conductivity of stearic acid and lauric acid-based composite PCM by 13.2 % and 30 %, respectively. The improvement in thermal conductivities was compromised with reductions in the latent heat of melting by 1.95 % and 5.91 % for silica and copper oxide nanoparticles loaded composite PCM [76].

While considering PCM for heat transfer applications, particularly when the involvement of humans becomes essential, it becomes mandatory to study its toxic behaviour. The toxicity of the PCM is determined by its effect on people via direct or indirect contact. Organic PCM based on paraffin and fatty acids might be harmful if not properly handled. Furthermore, incorrect disposal of organic PCMs may significantly affect human health and the environment [308]. The most researched PCM is paraffin wax because of its low toxicity, chemical modification ease, and broad transition temperature range [302]. According to Chandel and Agarwal [301], the US Food and Drug Administration have certified paraffin-based food-grade candles for use in medical, food, and cosmetics applications since they are non-toxic. In contrast, volatile compounds, including vinyl chloride and formaldehyde, have been identified in commercial-grade paraffin wax. Prolonged exposure to these chemical fumes may pose significant health risks, as they contain toluene and benzene, which are known carcinogens. It has been deemed that naturally derived PCMs, either from plants or oils such as beeswax, sheep fat and soy wax PCMs, are considered to be much safer for humans and the environment [106,107,110,309]. In a recent study, Kamrani et al. [310] recommended petroleum jelly for acne treatment. However, the paraffin family organic PCMs are difficult to dispose of compared to natural waxes. Fatty acids-based PCM were reported for variable toxicity [301,302]. The review article by Ameena et al. [311] highlights that lauric acid possesses various promising biomedical applications, such as antibacterial properties, antitumor effects, tissue engineering scaffolds, and drug delivery. Stearic acid is characterized by its non-toxic nature and cost-effectiveness [312], whereas myristic acid is noted for its low toxicity and cost [313]. Stearic and myristic acids have been noted for their potential use as food additives [312–314]. Park et al. [267] reported a detrimental effect of palmitic acid on human Chang liver cells following exposure to this fatty acid. Pascual et al. [315] demonstrated that dietary exposure to palmitic acid facilitated the development of tumorous cells in mice. These studies provide substantial evidence indicating that palmitic acid is highly toxic.

According to the discussion's conclusion, adding nanoparticles has been shown to increase the thermal conductivity of organic PCMs significantly, but it may also reduce heat capacity. Finding a balance or negotiating trade-offs among these properties is critical to selecting the most appropriate organic PCM based on thermal, physical, chemical, and economic characteristics, which may often conflict. This may be achieved by implementing a multi-criteria decision-making analysis, which is an intriguing topic for further investigation.

8. Discussion and challenges

PCMs are gaining much attention in systems where heat exchange phenomena prevail but are extensively utilized in solar thermal applications. Indeed, integrating PCM with solar desalination systems has a wide range of benefits, as we have learned in the above-detailed discourse of dialogue.

PCM allows solar still to function without interruption due to its ability to supply heat during odd times and maintain the thermal balance in the system to enable continuous evaporation of water. PCM with high thermal conductivity and high latent heat capacity is usually preferred for performing the solar still process. Studies suggested that paraffin wax, lauric acid, capric acid, and beeswax exhibit high thermal conductivity and have produced promising results in yield and productivity when integrated with different types of solar stills. High stability and durability in a PCM are essential due to the extended operational lifespan when incorporated with a solar still. In light of this, advanced hybrid PCMs or composite PCMs are currently being developed and employed in conjunction with various solar stills. Eutectic PCMs are state-of-the-art PCMs, also known as hybrid PCMs, have been in use with solar stills and have shown high potential for a wide range of thermal applications. Essentially, PCM should be non-toxic during its life span. It has been learned that some PCMs cause harmful effects on humans as well as an environment that can even lead to cancer (in the worst possible case). Therefore, before subjecting it to solar still applications, in vivo and in vitro test are essential. Various PCMs have an affinity towards metal and cause corrosion, consequently resulting in the degradation of metal containers. Hence, non-corrosive properties are highly desirable. For instance, beeswax, paraffin wax, and soy wax have been highly recommended due to their non-corrosive properties.

The cost of PCM is a significant factor in its selection for use in solar stills. Selecting a PCM that provides sufficient latent heat and excellent thermal conductivity, even at increased cost, may be justified if it significantly reduces the payback time of the solar still. To lower the production cost of PCM, it is possible to leverage renewable resources for its manufacturing. Ultimately, solar still would demonstrate greater sustainability and environmental friendliness. With the view of obtaining higher yield in solar still, several modifications have been adopted. These modifications are majorly performed in the design and material. For instance, new designs such as DSSS, PSS, TPSS, SSS, TSS, HSS, and TWSS have been proposed. However, among these, PSS has shown the highest yield due to the large surface area exposed to sunlight. In addition to improving the yield of the solar still, external attachments such as FPC, ETC, PVT and PTC have been integrated. Moreover, the vitality of the basin material is of utmost importance. Most of the basin materials utilized in solar still are made of aluminium, stainless steel, and copper, which play an essential role in significantly improving basin water temperature.

One of the main challenges of PCMs is their degradation over time due to repeated thermal cycling related to the recyclability and lifespan of organic PCMs in solar still. Organic PCMs are generally stable, but their performance can diminish after prolonged exposure to high temperatures, especially if they undergo many phase transitions, leading to changes in their melting points or reduced latent heat capacity. This degradation may affect solar stills' efficiency, requiring periodic PCM replacement. Another challenge is their recyclability; although organic PCMs are typically biodegradable and derived from renewable sources; the complex nature of some organic compounds makes large-scale recycling difficult. Additionally, impurities and environmental contamination during usage may affect their ability to be reused effectively. These factors combined can increase the maintenance costs and reduce the long-term sustainability of using organic PCMs in solar stills, making it essential to find solutions that enhance their durability and recycling processes to ensure their viability in sustainable applications.

9. Conclusions and future scopes

Energy storage usage in various applications has gained researchers' attention due to its versatility, ease of use, working range, etc. This review covers the research conducted over the last few years, i.e., (1) Phase change materials (PCMs), their selection and classification criteria, (2) Compatibility of PCMs with container materials, (3) application in solar distillation and solar still, (4) Role of organic PCMs in solar distillation (paraffin and non-paraffin). Organic PCMs are considered for solar thermal applications due to their high reliability and compatibility with container materials. Paraffin wax is widely used around the globe due to its ease of availability, wide range operating temperature, and compatibility with the materials. Due to their corrosion-resistant properties, aluminium, copper, brass, and stainless steel are reported as viable and sustainable material containers. Organic PCMs are readily accessible and exhibit exceptional properties, including non-corrosiveness, low supercooling, superior nucleation rates, and thermal and chemical stability. In contrast, inorganic PCMs are seldom employed due to their high corrosiveness, susceptibility to supercooling, and inherent instability. The highest distillate yield of more than 100 % was reported among non-paraffin organic PCMs for lauric and stearic acid compared to reference solar still due to their excellent thermal conductivity. However, their environmental effect restricts their widespread application for thermal energy storage. Using eco-friendly and cost-effective soy wax and beeswax as PCM have demonstrated the potential to increase the productivity of solar stills by over 100 %. It has been evident that the cylindrical shape of the PCM container is more effective than the spherical one. The cylindrical-shaped container for PCMs increases surface area and produces a higher distillate yield than other shapes. The PCM modified solar still can be beneficial in mitigating tons of carbon during its operation. Hence, PCM-modified solar still is way more efficient than several other modifications.

Eutectics PCMs are much more capable than conventional PCMs in performing effectively at various operating temperatures due to their wide range of thermophysical properties. Therefore, novel combinations must be investigated to unlock more possibilities that are beneficial in enhancing the productivity of the solar still. The latest water treatment techniques can be integrated with PCM to enhance affordability within the system. More accessibility can be achieved by carrying out research in PCM, such as salt hydrates and organic compounds-based water distillation systems. The placement of PCMs is a crucial parameter for improving yield. Researchers now lack in-depth details on the behavioural pattern at various placements of the PCM inside the solar still. Additionally, work can be carried out on the life cycle assessment of PCM in solar distillation systems and its compatibility with container material. The bulkiness of solar distillation systems is a considerable concern that must be addressed and resolved by making a compact and efficient design. Furthermore, multi-criteria decision-making techniques, statistical tools, and neural networks can be used in future studies to determine and optimize the concentrations of PCMs in different operational scenarios of solar stills.

CRediT authorship contribution statement

Akashdeep Negi: Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Data curation, Conceptualization. **Lalit Ranakoti:** Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Data curation, Conceptualization. **Rajesh P. Verma:** Writing – review & editing, Formal analysis, Data curation. **Vineet Kumar:** Writing – review & editing, Formal analysis, Data curation. **Prabhakar Bhandari:** Writing – review & editing, Formal analysis, Data curation. **Rohit Khargotra:** Writing – review & editing, Formal analysis, Data curation. **Tej Singh:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

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

Data availability

This is a review article; therefore, no data available in the manuscript.

References

[1] Naeem G, Asif M, Khalid M. Industry 4.0 digital technologies for the advancement of renewable energy: Functions, applications, potential and challenges. Energy Convers Manage: X 2024;24:100779.

[2] Lee S, Chang H, Lee J. Construction and demolition waste management and its impacts on the environment and human health: Moving forward sustainability enhancement. Sustain Cities Soc 2024;115:105855.

[3] Kannan N, Vakeesan D. Solar energy for future world:-A review. Renew Sustain Energy Rev 2016;62:1092–105.

[4] Lin Y, Jia Y, Alva G, Fang G. Review on thermal conductivity enhancement, thermal properties and applications of phase change materials in thermal energy storage. Renew Sustain Energy Rev 2018;82:2730–42.

[5] Gil A, Medrano M, Martorell I, Lázaro A, Dolado P, Zalba B, et al. State of the art on high temperature thermal energy storage for power generation. part 1—concepts, materials and modellization. Renew Sustain Energy Rev 2010;14:31–55.

[6] Mu L, Chen L, Lin L, Park YH, Wang H, Xu P, et al. An overview of solar still enhancement approaches for increased freshwater production rates from a thermal process perspective. Renew Sustain Energy Rev 2021;150:111458.

[7] https://www.wri.org/insights/highest-water-stressed-countries.

[8] Abdullah AS, Alawee WH, Shanmugan S, Omara ZM. Techniques used to maintain minimum water depth of solar stills for water desalination-A comparative review. Results Eng 2023;19:101301.

[9] Rejeb O, Yousef MS, Ghenai C, Hassan H, Bettayeb M. Investigation of a solar still behaviour using response surface methodology. Case Stud Therm Eng 2021;24:100816.

[10] Goel V, Saxena A, Kumar M, Thakur A, Sharma A, Bianco V. Potential of phase change materials and their effective use in solar thermal applications: A critical review. Appl Therm Eng 2022;219:119417.

[11] Bachchan AA, Nakshbandi SMI, Nandan G, Shukla AK, Dwivedi G, Singh AK. Productivity enhancement of solar still with phase change materials and water-absorbing material. Mater Today Proc 2021;38:438–43.

[12] Gude VG. Energy storage for desalination processes powered by renewable energy and waste heat sources. Appl Energy 2015;137:877–98.

[13] Chebli F, Mechighel F. Phase change materials: classification, use, phase transitions, and heat transfer enhancement techniques: a comprehensive review. J Therm Anal Calorim 2025. https://doi.org/10.1007/s10973-024-13877-z.

[14] Soares N, Costa JJ, Gaspar AR, Santos P. Review of passive PCM latent heat thermal energy storage systems towards buildings' energy efficiency. Energ Buildings 2013;59:82–103.

[15] Mohamed SA, Al-Sulaiman FA, Ibrahim NI, Zahir MH, Al-Ahmed A, Saidur R, et al. A review on current status and challenges of inorganic phase change materials for thermal energy storage systems. Renew Sustain Energy Rev 2017;70:1072–89.

[16] Alva G, Liu L, Huang X, Fang G. Thermal energy storage materials and systems for solar energy applications. Renew Sustain Energy Rev 2017;68:693–706.

[17] Kalidasan B, Pandey AK, Syed S, Samykano M, Thirugnanasambandam M, Saidur R. Phase change materials integrated solar thermal energy systems: Global trends and current practices in experimental approaches. J Storage Mater 2020;27:101118.

[18] Sharma A, Tyagi VV, Chen CR, Buddhi D. Review on thermal energy storage with phase change materials and applications. Renew Sustain Energy Rev 2009;13:318–45.

[19] Palanikumar G, Shanmugan S, Chithambaram V, Gorjian S, Pruncu CI, Essa FA, et al. Thermal investigation of a solar box-type cooker with nanocomposite phase change materials using flexible thermography. Renew Energy 2021;178:260–82.

[20] Prabu AS, Chithambaram V, Shanmugan S, Cavaliere P, Gorjian S, Aissa A, et al. The performance enhancement of solar cooker integrated with photovoltaic module and evacuated tubes using ZnO/Acalypha Indica leaf extract: response surface study analysis. Environ Sci Pollut Res 2023;30:15082–101.

[21] Palanikumar G, Shanmugan S, Janarthanan B, Sangavi R, Geethanjali P. Energy and environment control to box type solar cooker and nanoparticles mixed bar plate coating with effect of thermal image cooking pot. Mater Today Proc 2019;18:1243–55.

[22] Rathore PKS, Shukla SK. Enhanced thermophysical properties of organic PCM through shape stabilization for thermal energy storage in buildings: A state of the art review. Energ Buildings 2021;236:110799.

[23] Shukla A, Buddhi D, Sawhney RL. Solar water heaters with phase change material thermal energy storage medium: A review. Renew Sustain Energy Rev 2009;13:2119–25.

[24] Prasad DM, Senthilkumar R, Lakshmanarao G, Krishnan S, Prasad BS. A critical review on thermal energy storage materials and systems for solar applications. AIMS Energy 2019;7:507–26.

[25] Said Z, Pandey AK, Tiwari AK, Kalidasan B, Jamil F, Thakur AK, et al. Nano-enhanced phase change materials: Fundamentals and applications. Prog Energy Combust Sci 2024;104:101162.

[26] Ehms JHN, Oliveski RDC, Rocha LAO, Biserni C, Garai M. Fixed grid numerical models for solidification and melting of phase change materials (PCMs). Appl Sci 2019;9:4334.

[27] Kumar A, Shukla SK. A review on thermal energy storage unit for solar thermal power plant application. Energy Procedia 2015;74:462–9.

[28] Junaid MF, Rehman Z, Čekon M, Čurpek J, Farooq R, Cui H, et al. Inorganic phase change materials in thermal energy storage: A review on perspectives and technological advances in building applications. Energ Buildings 2021;252:111443.

[29] Benchara EH, Jennah S, Belouggadia N, Mansouri K, Bouattane O. Thermal energy storage by phase change materials suitable for solar water heaters: An updated review. In: In 2020 IEEE 2nd International Conference on Electronics, Control, Optimization and Computer Science (ICECOCS); 2020. p. 1–10.

[30] Tyagi VV, Chopra K, Sharma RK, Pandey AK, Tyagi SK, Ahmad MS, et al. A comprehensive review on phase change materials for heat storage applications: development, characterization, thermal and chemical stability. Sol Energy Mater Sol Cells 2022;234:111392.

[31] Farid M, Khudhair AM, Razack SAK, Al-Hallaj S. A Review on Phase Change Energy Storage: Materials and Applications. Energ Conver Manage 2004;45:1597–615.

[32] Jurczyk M, Spietz T, Czardybon A, Dobras S, Ignasiak K, Bartela Ł, et al. Review of thermal energy storage materials for application in large-scale integrated energy systems-methodology for matching heat storage solutions for given applications. Energies 2024;17(14):3544.

[33] Zhang H, Xu C, Fang G. Encapsulation of inorganic phase change thermal storage materials and its effect on thermophysical properties: A review. Sol Energy Mater Sol Cells 2022;241:111747.

[34] Khan Z, Khan Z, Ghafoor A. A review of performance enhancement of PCM based latent heat storage system within the context of materials, thermal stability and compatibility. Energ Conver Manage 2016;115:132–58.

[35] Safari A, Saidur R, Sulaiman FA, Xu Y, Dong J. A review on supercooling of Phase Change Materials in thermal energy storage systems. Renew Sustain Energy Rev 2017;70:905–19.

[36] Sharma RK, Ganesan P, Tyagi VV, Metselaar HSC, Sandaran SC. Developments in organic solid–liquid phase change materials and their applications in thermal energy storage. Energ Conver Manage 2015;95:193–228.

[37] Paul A, Baumhögger E, Dewerth MO, Dindar IH, Sonnenrein G, Vrabec J. Thermal conductivity of solid paraffins and several n-docosane compounds with graphite. J Therm Anal Calorim 2023;148:5687–94.

[38] Wang G, Ha DS, Wang KG. Harvesting environmental thermal energy using solid/liquid phase change materials. J Intell Mater Syst Struct 2018;29:1632–48.

[39] Jouhara H, Żabnieńska-Góra A, Khordehgah N, Ahmad D, Lipinski T. Latent thermal energy storage technologies and applications: A review. International Journal of Thermofluids 2020;5:100039.

[40] Sharma RK, Kumar A, Rakshit D. A phase change material (PCM) based novel retrofitting approach in the air conditioning system to reduce building energy demand. Appl Therm Eng 2024;238:121872.

[41] Das D, Sharma RK, Saikia P, Rakshit D. An integrated entropy-based multi-attribute decision-making model for phase change material selection and passive thermal management. Decision Analytics Journal 2021;1:100011.

[42] Sam MN, Caggiano A, Mankel C, Koenders E. A comparative study on the thermal energy storage performance of bio-based and paraffin-based PCMs using DSC procedures. Materials 2020;13:1705.

[43] Rehman UU, Ashiq M, Rafi MA, Malik U, Javid W, Amjad MUH. Investigating Energy-Saving Strategies: A Numerical Study of Translucent Insulation and Phase Change Materials in Windows. Engineering Proceedings 2023;45:12.

[44] Sharma A, Pitchumani R, Chauhan R. Melting and solidification performance investigation of latent heat storage unit designs for low-temperature solar thermal applications. J Storage Mater 2023;66:107323.

[45] Mekaddem N, Ali SB, Fois M, Hannachi A. Paraffin/ Expanded Perlite/Plaster as Thermal Energy Storage Composite. Energy Procedia 2019;157:1118–29.

[46] Soni K, Panwar NL. Revolutionizing thermal energy storage: An overview of porous support materials for advanced composite Phase Change Materials (PCMs). Progress in Engineering Science 2024;1:100023.

[47] Sharma A, Chauhan R, Kallioğlu MA, Chinnasamy V, Singh T. A review of phase change materials (PCMs) for thermal storage in solar air heating systems. Mater Today Proc 2021;44:4357–63.

[48] Rehman T, Ali HM, Saieed A, Pao W, Ali M. Copper foam/PCMs based heat sinks: An experimental study for electronic cooling systems. Int J Heat Mass Transf 2018;127:381–93.

[49] Sharma S, Sellami N, Tahir AA, Mallick TK, Bhakar R. Performance improvement of a CPV system: experimental investigation into passive cooling with phase change materials. Energies 2021;14:3550.

[50] Palaniappan M, El-Shafay AS, Shanmugan S. Improving heat retention properties of steeped M-shape basin solar distillers utilizing paraffin RT50-enhanced silver nanoparticles and Manihot esculenta extracts. Desalination 2024;586:117836.

[51] Al-Mudhafar AH, Nowakowski AF, Nicolleau FC. Enhancing the thermal performance of PCM in a shell and tube latent heat energy storage system by utilizing innovative fins. Energy Rep 2021;7:120–6.

[52] Sharma A, Chauhan R. Integrated and separate collector storage type low-temperature solar water heating systems with latent heat storage: A review. Sustainable Energy Technol Assess 2022;51:101935.

[53] Murali G, Ramani P, Murugan M, Elumalai PV, Goud NUR, Prabhakar S. Improved solar still productivity using PCM and nano-PCM composites integerated energy storage. Sci Rep 2024;14:15609.

[54] Fayaz H, Ramesh S, Afzal A, Ağbulut Ü, Khan SA, Asif M, et al. Investigation of numerical phase transition of nano-enhanced SiC/paraffin wax PCM in solar-assisted water desalination system. Therm Sci Eng Prog 2024;50:102528.

[55] Banoqitah E, Sathyamurthy R, Moustafa EB, Fujii M, Sudalaimuthu P, Djouider F, et al. Enhancement and prediction of a stepped solar still productivity integrated with paraffin wax enriched with nano-additives. Case Stud Therm Eng 2023;49:103215.

[56] Kabeel AE, El-Samadony YAF, El-Maghlany WM. Comparative study on the solar still performance utilizing different PCM. Desalination 2018;432:89–96.

[57] Thakur V, Kumar N. Natural and sustainable thermal storage solution for solar distillation system using sensible fiber material and latent PCM: Enhanced energy storage application. Heat Transfer 2023;53:4052–83.

[58] Sharma P, Birla SK. Simulation and experimental analysis of PCM-enhanced solar stills using CMS. J Storage Mater 2024;103:114318.

[59] Chaichan MT, Kazem HA, Al-Waeli AHA, Sopian K. Controlling the melting and solidification points temperature of PCMs on the performance and economic return of the water-cooled photovoltaic thermal system. Sol Energy 2021;224:1344–57.

[60] Abu-Hamdeh NH, Alnefaie KA. Assessment of thermal performance of PCM in latent heat storage system for different applications. Sol Energy 2019;177:317–23.

[61] Dai J, Ma F, Fu Z, Li C, Jia M, Shi K, et al. Applicability assessment of stearic acid/palmitic acid binary eutectic phase change material in cooling pavement. Renew Energy 2021;175:748–59.

[62] Sharma A, Ding C, Kim SC, Chauhan R. Investigation and optimization of solidification performance of concentration tube type latent heat storage unit with herringbone wavy fin designs. Appl Therm Eng 2023;222:119924.

[63] Gür M, Gürgenç E, Coşanay H, Öztop HF. Novel nano-Y_2O_3/myristic acid nanocomposite PCM for cooling performances of electronic device with various fin designs. J Storage Mater 2024;100:113646.

[64] Ismail M, Alkhazaleh AH, Ali M, Ali AM, Masri J. Development and Characterisation of Myristic Acid-Paraffin Wax, Silica Fume and Zinc Oxide Cementitious Composites for Thermal Control in Buildings. Case Stud Therm Eng 2024;63:105283.

[65] Kant K, Shukla A, Sharma A. Performance evaluation of fatty acids as phase change material for thermal energy storage. J Storage Mater 2016;6:153–62.

[66] Ao C, Yan S, Zhao S, Hu W, Zhao L, Wu Y. Stearic acid/expanded graphite composite phase change material with high thermal conductivity for thermal energy storage. Energy Rep 2022;8:4834–43.

[67] Boldoo T, Chinnasamy V, You N, Cho H. Experimental analysis on thermal energy storage performance of micro-encapsulated stearic acid and stearyl alcohol PCM slurries; A comparative study. J Storage Mater 2023;73:109218.

[68] Zhou D, Zhou Y, Yuan J, Liu Y. Palmitic acid-stearic acid/expanded graphite as form-stable composite phase-change material for latent heat thermal energy storage. J Nanomater 2020;2020:1648080.

[69] Lu W, Yu A, Dong H, He Z, Liang Y, Liu W, et al. High-performance palmityl palmitate phase change microcapsules for thermal energy storage and thermal regulation. Energy 2023;274:127336.

[70] Wang C, Wang T, Hu Z, Cai Z. Facile synthesis and thermal performance of cety palmitate/nickel foam composite phase change materials for thermal energy storage. J Storage Mater 2020;28:101179.

[71] Singh P, Sharma RK, Hekimoğlu G, Sarı A, Gencel O, Tyagi VV. Expanded waste glass/methyl palmitate/carbon nanofibers as effective shape stabilized and thermal enhanced composite phase change material for thermal energy storage. J Storage Mater 2023;64:107205.

[72] Rasulov SM, Abdulagatov IM. PVT, saturated liquid density and vapor-pressure measurements of main components of the biofuels at high temperatures and high pressures: Methyl palmitate. Fuel 2018;218:282–94.

[73] Yin S, Lu M, Liu C, Tong L, Wang L, Ding Y. Fabrication and thermal properties of capric–stearic acid eutectic/nano-SiO_2 phase change material with expanded graphite and CuO for thermal energy storage. J Storage Mater 2024;77:110025.

[74] Pugalenthi S, Chellapandian M, Dharmaraj JJJ, Devaraj J, Arunachelam N, Singh SB. Enhancing the thermal transport property of eutectic lauric-stearic acid based phase change material with silicon carbide nanoparticles for usage in battery thermal management system. J Storage Mater 2024;84:110890.

[75] Sari A, Kaygusuz K. Thermal performance of a eutectic mixture of lauric and stearic acids as PCM encapsulated in the annulus of two concentric pipes. Sol Energy 2002;72:493–504.

[76] Tan Q, Liu H, Shi Y, Zhang M, Yu B, Zhang Y. Lauric acid/stearic acid/nano-particles composite phase change materials for energy storage in buildings. J Storage Mater 2024;76:109664.

[77] Qiao Y, Gao Z, Gu X, Zhang X. Preparation and characterization of polyurethane/lauric acid-stearic acid as form-stable phase change materials with a wide phase transition temperature range. Mater Lett 2024;361:136120.

[78] Cárdenas-Ramírez C, Gómez MA, Jaramillo F. Comprehensive analysis of the thermal properties of capric-myristic, lauric-myristic and palmitic-stearic acids and their shape-stabilization in an inorganic support. J Storage Mater 2021;34:102015.

[79] Karthikeyan K, Mariappan V, Kalidoss P, Anish R, Sarafoji P, Reddy JV, et al. Preparation and thermal characterization of capric-myristic acid binary eutectic mixture with silver–antimony tin oxide and silver-graphane nanoplatelets hybrid-nanoparticles as phase change material for building applications. Mater Lett 2022;328:133086.

[80] Hou Y, Ma Fe, Fu Z, Li C, An Q, Zhu C, et al. Encapsulation of stearic-palmitic acid in alkali-activated coconut shell and corn cob biochar to optimize energy storage. J Energy Storage 2023;66:107418.

[81] https://www.atamanchemicals.com/stearic-palmitic-acid-c18-c16_u30006/.

[82] Roxas-Dimaano MN, Watanabe T. The capric and lauric acid mixture with chemical additives as latent heat storage materials for cooling application. Energy 2002;27:869–88.

[83] Zhou Q, Zhang Y, Guo H, Li Q, Li D. Research on the Thermo Physical Properties of Lauric Acid-Capric Acid Binary Mixture Phase Change Materials. Appl Mech Mater 2012;226–228:1704–8.

[84] Liu S, Gao W, Deng J, Wang M, Zhou M, Liang H. Capric-lauric & capric-palmitic/modified bentonite composite as phase change materials for thermal energy storage. J Storage Mater 2024;99:113315.

[85] Browne MC, Lawlor K, Kelly A, Norton B, Cormack SJM. Indoor characterisation of a photovoltaic/thermal phase change material system. Energy Procedia 2015;70:163–71.

[86] Sarı A, Bicer A, Al-Ahmed A, Al-Sulaiman FA, Zahir MH, Mohamed SA. Silica fume/capric acid-palmitic acid composite phase change material doped with CNTs for thermal energy storage. Sol Energy Mater Sol Cells 2018;179:353–61.

[87] Tan N, Xie T, Hu P, Feng Y, Li Q, Zhao S, et al. Preparation and characterization of capric-palmitic acids eutectics/silica xerogel/exfoliated graphite nanoplatelets form-stable phase change materials. J Storage Mater 2021;34:102016.

[88] He Q, Fei H, Zhou J, Du W, Pan Y, Liang X. Preparation and characteristics of lauric acid-myristic acid-based ternary phase change materials for thermal storage. Mater Today Commun 2022;32:104058.

[89] Zhang X, Huang Z, Yin Z, Zhang W, Huang Y, Liu Y, et al. Form stable composite phase change materials from palmitic-lauric acid eutectic mixture and carbonized abandoned rice: Preparation, characterization, and thermal conductivity enhancement. Energ Buildings 2017;154:46–54.

[90] Xu C, Wang W, Zhang H, Fang G. Thermal properties of lauric acid-palmitic acid eutectics/polyvinyl butyral/carbon nanofibers as shape-stable phase change materials. Thermochim Acta 2022;715:179300.

[91] Fauzi H, Metselaar HSC, Mahlia TMI, Silakhori M, Nur H. Phase change material: Optimizing the thermal properties and thermal conductivity of myristic acid/palmitic acid eutectic mixture with acid-based surfactants. Appl Therm Eng 2013;60:261–5.

[92] Alva G, Huang X, Liu L, Fang G. Synthesis and characterization of microencapsulated myristic acid–palmitic acid eutectic mixture as phase change material for thermal energy storage. Appl Energy 2017;203:677–85.

[93] Zhou J, Fei H, He Q, Li P, Pan Y, Liang X. Structural characteristics and thermal performances of lauric-myristic-palmitic acid introduced into modified water hyacinth porous biochar for thermal energy storage. Sci Total Environ 2023;882:163670.

[94] Jebasingh BE. Exfoliation of graphite by solar irradiation and investigate their thermal property on capric–myristic–palmitic acid/exfoliated graphite composite as phase change material (PCM) for energy storage. J Storage Mater 2016;5:70–6.

[95] Yang X, Yuan Y, Zhang N, Cao X, Liu C. Preparation and properties of myristic–palmitic–stearic acid/expanded graphite composites as phase change materials for energy storage. Sol Energy 2014;99:259–66.

[96] Zhang N, Yuan Y, Yuan Y, Li T, Cao X. Lauric-palmitic-stearic acid/expanded perlite composite as form-stable phase change material: Preparation and thermal properties. Energ Buildings 2014;82:505–11.

[97] Zhang H, Gao X, Chen C, Xu T, Fang Y, Zhang Z. A capric-palmitic-stearic acid ternary eutectic mixture/expanded graphite composite phase change material for thermal energy storage. Compos A Appl Sci Manuf 2016;87:138–45.

[98] Rathore PKS, Gupta KK, Patel B, Sharma RK, Gupta NK. Beeswax as a potential replacement of paraffin wax as shape stabilized solar thermal energy storage material: An experimental study. J Storage Mater 2023;68:107714.

[99] Putra N, Sandi AF, Ariantara B, Abdullah N, Mahlia TMI. Performance of beeswax phase change material (PCM) and heat pipe as passive battery cooling system for electric vehicles. Case Stud Therm Eng 2020;21:100655.

[100] Murthy BVR, Gumtapure V. Thermo-physical analysis of natural shellac wax as novel bio-phase change material for thermal energy storage applications. J Storage Mater 2020;29:101390.

[101] Murthy BVR, Thanaiah K, Gumtapure V. Experimental investigation of shellac wax as potential bio-phase change material for medium temperature solar thermal energy storage applications. Sol Energy 2022;231:1002–14.

[102] Bartali R, Bolognese M, Fronza N, Prattico L, Zanetti A, Osorio T, et al. Study on carnauba wax as phase-change material integrated in evacuated-tube collector for solar-thermal heat production. Clean Energy 2023;7:547–54.

[103] Xia M, Yuan Y, Zhao X, Cao X, Tang Z. Cold storage condensation heat recovery system with a novel composite phase change material. Appl Energy 2016;175:259–68.

[104] Ruguo Z, Hua Z, Hong Z, Ying F, Kun L, Wenwen Z. Thermal analysis of four insect waxes based on differential scanning calorimetry (DSC). Procedia Eng 2011;18:101–6.

[105] https://vilf.de/wp-content/uploads/pdfs/Naturwachse_VILF_1_.pdf.

[106] Szymanskia P, Paluch R. Experimental investigation on heat pipes supported by soy wax and lauric acid for electronics cooling. J Storage Mater 2024;83:110813.

[107] Gunawan Y, Trisnadewi T, Putra N, Akhiriyanto N, Trylucky DN. Performance of natural wax as phase change material for intermittent solar energy storage in agricultural drying: An experimental study. Sol Energy 2023;251:158–70.

[108] Trisnadewi T, Kusrini E, Nurjaya DM, Putra N, Mahlia TMI. Experimental analysis of natural wax as phase change material by thermal cycling test using thermoelectric system. J Storage Mater 2021;40:102703.

[109] Cao F, Zheng Y, Chen C-H, Bonner R. Thermal energy storage with tunable melting point phase change materials. Proceedings of the 16th International Heat Transfer Conference, IHTC-16 2018:IHTC16-22260.

[110] Sharshir SW, Omara MA, Elsisi G, Joseph A, Kandeal AW, Ali A, et al. Thermo-economic performance improvement of hemispherical solar still using wick material with V-corrugated basin and two different energy storage materials. Sol Energy 2023;249:336–52.

[111] Ushak S, Suárez M, Véliz S, Fernández AG, Flores E, Galleguillos HR. Characterization of calcium chloride tetrahydrate as a phase change material and thermodynamic analysis of the results. Renew Energy 2016;95:213–24.

[112] Yan T, Zhang H. A critical review of salt hydrates as thermochemical sorption heat storage materials: Thermophysical properties and reaction kinetics. Sol Energy 2022;242:157–83.

[113] Lu F, Chen W, Hu S, Chen L, Sharshir SW, Dong C, et al. Achieving a smart thermal management for lithium-ion batteries by electrically-controlled crystallization of supercooled calcium chloride hexahydrate solution. Appl Energy 2024;364:123180.

[114] Işık SK, El E. Experimental investigation of distilled water production performance of conventional solar stills using $CaCl_2{\cdot}6H_2O$ phase change material reinforced with $SrCl_2{\cdot}6H_2O$ and graphene-based nanoparticles. Case Stud Therm Eng 2024;62:105184.

[115] Kenisarin M, Mahkamov K. Salt hydrates as latent heat storage materials: Thermophysical properties and costs. Sol Energy Mater Sol Cells 2016;145:255–86.

[116] Man X, Lu H, Xu Q, Wang C, Ling Z. Review on the thermal property enhancement of inorganic salt hydrate phase change materials. J Storage Mater 2023;72:108699.

[117] Ding X, Huang J, Zhu F, Wang Y, Shao Y, Li X, et al. Study on energy storage performance of thermally enhanced composite phase change material of calcium nitrate tetrahydrate. J Storage Mater 2022;52:104879.

[118] Ahmed S, Hoe A, Alamo F, Turner N, Shamberger PJ. Experimental determination of high energy density lithium nitrate hydrate eutectics. J Storage Mater 2022;52:104754.

[119] Boucetta C, Chibani A, Hebbir N, Merouani S, Haddad MAN, Badji R. Thermal performance and flash point analyses of concentrator photovoltaic (CPV) system using multiple types of PCMs and various panel inclination angles under the effect of a constant heat flux. Journal of Engineering Research 2024. https://doi.org/10.1016/j.jer.2024.09.018.

[120] Majd AE, Sair S, Ousaleh HA, Berardi U, Moulakhnif K, Belouaggadia N, et al. Advancing PCM research in building efficiency: A comprehensive investigation into PCM selection and critical integration strategies. Journal of Building Engineering 2024;96:110485.

[121] Islam MN, Hossain MN, Ahmed DH. Investigation of phase-change materials for interior temperature regulation in public transport. Clean Energy 2022;6:178–92.

[122] Kurdi A, Almoatham N, Mirza M, Ballweg T, Alkahlan B. Potential phase change materials in building wall construction-a review. Materials 2021;14:5328.

[123] Kalidasan B, Pandey AK, Saidur R, Tyagi SK, Mishra YK. Experimental evaluation of binary and ternary eutectic phase change material for sustainable thermal energy storage. J Storage Mater 2023;68:107707.

[124] Canbazoğlu S, Şahinaslan A, Ekmekyapar A, Akarsu ÝGAF. Enhancement of solar thermal energy storage performance using sodium thiosulfate pentahydrate of a conventional solar water-heating system. Energ Buildings 2005;37:235–42.

[125] Rakshamuthu S, Jegan S, Benyameen JJ, Selvakumar V, Anandeeswaran K, Iyahraja S. Experimental analysis of small size solar dryer with phase change materials for food preservation. J Storage Mater 2021;33:102095.

[126] Ahmed S, Ibbotson D, Somodi C, Shamberger PJ. Zinc nitrate hexahydrate pseudobinary eutectics for near-room temperature thermal energy storage. ACS Appl Eng Mater 2024;2:530–41.

[127] Kalidasan B, Pandey AK, Saidur R, Kothari R, Sharma K, Tyagi VV. Eco-friendly coconut shell biochar based nano-inclusion for sustainable energy storage of binary eutectic salt hydrate phase change materials. Sol Energy Mater Sol Cells 2023;262:112534.

[128] Fu W, Zou T, Liang X, Wang S, Gao X, Zhang Z, et al. Characterization and thermal performance of microencapsulated sodium thiosulfate pentahydrate as phase change material for thermal energy storage. Sol Energy Mater Sol Cells 2019;193:149–56.

[129] Rabady RI, Malkawi DS. Thermal conductivity enhancement of sodium thiosulfate pentahydrate by adding carbon nano-tubes/graphite nano-particles. J Storage Mater 2020;27:101166.

[130] Lin W, Zhang W, Ling Z, Fang X, Zhang Z. Experimental study of the thermal performance of a novel plate type heat exchanger with phase change material. Appl Therm Eng 2020;178:115630.

[131] Xu T, Gunasekara SN, Chiu JN, Palm B, Sawalha S. Thermal behavior of a sodium acetate trihydrate-based PCM: T-history and full-scale tests. Appl Energy 2020;261:114432.

[132] Işık SK. Optimizing thermal performance of sodium acetate trihydrate phase-change-materials through synergistic effects of binary graphene nanoadditives for prolonged hot beverage maintenance. Case Stud Therm Eng 2024;62:105187.

[133] Dannemand M, Delgado M, Lazaro A, Penalosa C, Gundlach C, Trinderup C, et al. Porosity and density measurements of sodium acetate trihydrate for thermal energy storage. Appl Therm Eng 2018;131:707–14.

[134] Wang Q, Wang J, Chen Y, Zhao CY. Experimental investigation of barium hydroxide octahydrate as latent heat storage materials. Sol Energy 2019;177:99–107.

[135] Zhang Y, Zhang X, Ji Ju. Experimental study on powdered expansion of barium hydroxide octahydrate crystal. J Mol Liq 2019;296:111907.

[136] Song K, Jiang Z, He F, Li Y, He Z, Li Y, et al. Supercooling degree decrease of barium hydroxide octahydrate employing 3D porous silver foam as supporting material. Colloids Surf A Physicochem Eng Asp 2024;684:133138.

[137] Negi A, Ranakoti L, Bhandari P, Khargotra R, Singh T. Thermo-physical characteristics and storage material compatibility in nano-enhanced phase change materials for solar distillation applications: A critical assessment. Sol Energy Mater Sol Cells 2024;271:112870.

[138] Ferrer G, Solé A, Barreneche C, Martorell I, Cabeza LF. Corrosion of metal containers for use in PCM energy storage. Renew Energy 2015;76:465–9.

[139] Farrell AJ, Norton B, Kennedy DM. Corrosive effects of salt hydrate phase change materials used with aluminium and copper. J Mater Process Technol 2006;175:198–205.

[140] E. Ghali V.S. Sastri M. Elboujdaini J. Wiley L. Sons Corrosion Prevention and Protection: Practical Solutions 2007 10.1002/9780470024546.

[141] Krishna DJ, Shinde A. Step by step methodology for the assessment of metal corrosion rate with PCMs suitable for low temperature heat storage applications. Mater Today Proc 2017;4:10039–42.

[142] Rostami S, Afrand M, Shahsavar A, Sheikholeslami M, Kalbasi R, Aghakhani S, et al. A review of melting and freezing processes of PCM/nano-PCM and their application in energy storage. Energy 2020;211:118698.

[143] Dursun T, Soutis C. Recent developments in advanced aircraft aluminium alloys. Mater Des 2014;56:862–71.

[144] Davis J.R. Surface Engineering for Corrosion and Wear Resistance 2001 ASM international.

[145] Sadeghi G. Energy storage on demand: Thermal energy storage development, materials, design, and integration challenges. Energy Storage Mater 2022;46:192–222.

[146] Vasu A, Hagos FY, Mamat MMNR, Azmi WH, Abdullah AA, Ibrahim TK. Corrosion effect of phase change materials in solar thermal energy storage application. Renew Sustain Energy Rev 2017;76:19–33.

[147] Rolka P, Karwacki J, Jaworski M. Compatibility Tests between Three Commercially Available Organic PCMs and Metals Typically Used in Fin-and-Tube Heat Exchangers. Materials 2021;14:5172.

[148] Ossai CI. Advances in asset management techniques: An overview of corrosion mechanisms and mitigation strategies for oil and gas pipelines. International Scholarly Research Notices 2012;2012:570143.

[149] Brahma B, Narzary R, Baruah DC. Acetamide for latent heat storage: Thermal stability and metal corrosivity with varying thermal cycles. Renew Energy 2020;145:1932–40.

[150] Rathod MK, Banerjee J. Thermal stability of phase change materials used in latent heat energy storage systems: A review. Renew Sustain Energy Rev 2013;18:246–58.

[151] Wang R, Hertwich E, Zimmerman JB. (Virtual) water flows uphill toward money. Environ Sci Tech 2016;50:12320–30.

[152] Sangeetha A, Shanmugan S, Alrubaie AJ, Jaber MM, Panchal H, Attia MEH, et al. A review on PCM and nanofluid for various productivity enhancement methods for double slope solar still: Future challenge and current water issues. Desalination 2023;551:116367.

[153] Rathi BS, Kumar PS. Application of adsorption process for effective removal of emerging contaminants from water and wastewater. Environ Pollut 2021;280:116995.

[154] Saleh TA, Mustaqeem M, Khaled M. Water treatment technologies in removing heavy metal ions from wastewater: A review. Environ Nanotechnol Monit Manage 2022;17:100617.

[155] Yuan ZY, Li YF, Li TY, Yao JL, Zhang JF, Wang XM. Identifying key residual aluminum species responsible for aggravation of nanofiltration membrane fouling in drinking water treatment. J Membr Sci 2022;659:120833.

[156] Al-Raad AA, Hanafiah MM, Naje AS, Ajeel MA. Optimized parameters of the electrocoagulation process using a novel reactor with rotating anode for saline water treatment. Environ Pollut 2020;265:115049.

[157] Gogoi JK, Sharma P, Talekar GV, Mutnuri S. Effect of salt dosage on the performance efficiency of the electro-oxidation process employed for integrated blackwater treatment. Int J Environ Sci Technol 2022:1–12.

[158] Partal R, Basturk I, Hocaoglu SM, Baban A, Yilmaz E. Recovery of water and reusable salt solution from reverse osmosis brine in textile industry: A case study. Water Resour Ind 2022;27:100174.

[159] Arunkumar T, Sathyamurthy R, Denkenberger D, Lee SJ. Solar distillation meets the real world: a review of solar stills purifying real wastewater and seawater. Environ Sci Pollut Res 2022;29:22860–84.

[160] Kanchana V, Kumar PM, Kumar PS, Kathir I, Thirumalai R, Priya D, et al. Investigating underground water salinity in east coastline of Tamil Nadu, India and improving its quality through solar assisted desalination. Urban Clim 2023;49:101440.

[161] Lauvandy AF, Raihananda FA, Estefan MJ, Damanik WS, Mu’min GF, Juangsa FB, et al. Application of a low-cost floating solar still in Indonesia. Energy Sustain Dev 2024;79:101410.

[162] Uthappan K, Murugesan S, Karuppasamy G, Thangavel K. Experimental investigation of single slope solar still for culinary wastewater treatment. Sol Compass 2024;12:100095.

[163] Pathak S, Jeyaraj T, Kumar P. A CFD and experimental analysis of a double-slope solar still with channel integration. Appl Therm Eng 2025;258:124538.

[164] Suraparaju SK, Peddojula MK, Samykano M, El-Sebaey MS, Kadambari CSVK, Budala SB, et al. Enhancing the productivity of pyramid solar still utilizing repurposed finishing pads as cost-effective porous material. Desalin Water Treat 2024;320:100733.

[165] Bait O. A critical review on triangular pyramid, weir–type, spherical, and hemispherical solar water distiller conceptions. Sol Energy 2024;269:112322.

[166] El-Sebaey MS, Alrashidi Ah, Suraparaju SK, Sathyamurthy R, Essa FA, Singh AK, et al. Stepped solar stills: a comprehensive review of design, performance, and optimization strategies for sustainable water desalination. Sol Energy 2024;284:113077.

[167] Elamy MI, Mohammed SA, Basem A, Alawee WH, Aldabesh A, Abdullah AS, et al. Augmenting thermal performance in tubular solar stills: A multifaceted strategy with wick cords, integrated baffles, reflectors, and nano-PCM. Results Eng 2024;23:102771.

[168] Kabeel AE, Harby K, Abdelgaied M, Eisa A. A comprehensive review of tubular solar still designs, performance, and economic analysis. J Clean Prod 2020;246:119030.

[169] Alqsair UF, Abdullah AS, Younes MM, Omara ZM, Essa FA. Augmenting hemispherical solar still performance: A multifaceted approach with reflectors, external condenser, advanced wick materials, and nano-PCM integration. Case Stud Therm Eng 2024;61:104890.

[170] Rashid FL, Al-Obaidi MA, Hammoodi KA, Mahdi AJ, Kadhim SA, Chaichan MT, et al. Innovations and ongoing advancements of the wick type solar still: A review. Results Eng 2024;24:103049.

[171] Sivakumar CK, Robinson Y, Gnanaraj SJP, Jithendra KB. Analysis of the performance of V-type solar stills coupled with flat plate collectors and the potential use of artificial intelligence. Desalin Water Treat 2024;318:100365.

[172] Abdullah AS, Joseph A, Abdelaziz GB, Edreis EMA, Attia MEH, Alawee WH, et al. Harnessing evacuated tube technology for enhanced solar still: A comprehensive review. Results Eng 2024;24:103335.

[173] Farghaly MB, Alahmadi RN, Sarhan HH, Abdelghany ES. Experimental study of simultaneous effect of evacuated tube collectors coupled with parabolic reflectors on traditional single slope solar still efficiency. Case Stud Therm Eng 2023;49:103304.

[174] Amin M, Umar H, Ginting SF, Amir F, Rizal TA, Septiadi WN, et al. Enhancing solar distillation through beeswax-infused tubular solar still with a heat exchanger using parabolic trough collector. J Storage Mater 2024;86:111262.

[175] Shanmugan S, Hammoodi KA, Eswarlal T, Selvaraju P, Bendoukha S, Barhoumi N, et al. A technical appraisal of solar photovoltaic-integrated single slope single basin solar still for simultaneous energy and water generation. Case Stud Therm Eng 2024;54:104032.

[176] Saleh B, Ahmed MH, Shanmugan S, Elsheikh AH, El-Sebaey MS, Stephen MT, et al. Enhancing desalination performance of a stepped solar still using nano-enhanced phase change material and condenser integration. Sol Energy Mater Sol Cells 2024;277:113141.

[177] Elamy MI, Mohammed SA, Basem A, Alawee WH, Abdullah AS, Aldabesh A, et al. Enhancing coiled solar still performance with vertical wick distiller, reflectors, nanomaterial-infused PCM, and condenser integration. Case Stud Therm Eng 2024;61:104912.

[178] Daif MM, Emam M, Abdelrahman MA, Attia AAA, Soliman AMA. Experimental investigation of a sun tracking concentrated solar still with economic analysis. Appl Water Sci 2024;14:136.

[179] Shanmugan S, Djuansjah J, Ahmadein M, Alsaleh NA, Parsa SM, Elsheikh AH. Chemical potential of different phases inside the pyramid stepped basin solar still through Gibbs free energy. Case Stud Therm Eng 2023;49:103277.

[180] Ghandourah EI, Sangeetha A, Shanmugan S, Zayed ME, Moustafa EB, Tounsi A, et al. Performance assessment of a novel solar distiller with a double slope basin covered by coated wick with lanthanum cobalt oxide nanoparticles. Case Stud Therm Eng 2022;32:101859.

[181] Kumar R, Tripathi P, Ongar B, Khidolda Y, Omara ZM, Abdullah AS, et al. Experimental study on double effect solar distiller using bioactivity nanoparticles with analysis of thermo-economic and enviro-economical. Case Stud Therm Eng 2023;47:103045.

[182] Sangeetha A, Shanmugan S, Gorjian S. Experimental evaluation and thermodynamic Gibbs free energy analysis of a double-slope U-shaped stepped basin solar still using activated carbon with ZnO nanoparticles. J Clean Prod 2022;380:135118.

[183] Tan JH, Liew YY, Bahar R, Jun HK, Low J. Enhancing solar still productivity in tropical climate with conductive particle-assisted phase change material. Sol Energy Mater Sol Cells 2025;279:113227.

[184] Saad FO, Mankai S, Madiouli J, Chemkhi S, Shigidi I, Khan MI. Effect of phase change materials melting temperature on improving single slope solar still productivity. J Storage Mater 2024;97:112927.

[185] Xu B, Zhao X, Zuo X, Yang H. Progress of phase change materials in solar water desalination system: A review. Sol Energy Mater Sol Cells 2024;271:112874.

[186] Sonker VK, Sharma P, Ram R, Sarkar A. A CFD simulation analysis of the effects of PCM and nanoparticles stored in copper cylinders inside a solar still. J Storage Mater 2025;108:115091.

[187] Omara ZM, Ahmed MMZ, Alawee WH, Shanmugan S, Elashmawy M. A comprehensive review of nano-enhanced phase change materials on solar stills with scientometric analysis. Results Eng 2024;22:102088.

[188] Rozanna D, Chuah TG, Salmiah A, Choong TS, Sa'Ari M. Fatty acids as phase change materials (PCMs) for thermal energy storage: a review. Int J Green Energy 2005;1:495–513.

[189] No SY. Application of hydrotreated vegetable oil from triglyceride based biomass to CI engines-A review. Fuel 2014;115:88–96.

[190] Sarı A, Kaygusuz K. Some fatty acids used for latent heat storage: thermal stability and corrosion of metals with respect to thermal cycling. Renew Energy 2003;28:939–48.

[191] Sarı A, Sarı H, Önal A. Thermal properties and thermal reliability of eutectic mixtures of some fatty acids as latent heat storage materials. Energ Conver Manage 2004;45:365–76.

[192] Dincer I. Thermal energy storage systems as a key technology in energy conservation. Int J Energy Res 2002;26:567–88.

[193] Lane GA. Low temperature heat storage with phase change materials. Int J Ambient Energy 1980;1:155–68.

[194] Dayrit FM. Lauric acid is a medium-chain fatty acid, coconut oil is a medium-chain triglyceride. Philippine Journal of Science 2014;143:157–66.

[195] Kateshia J, Lakhera V. A comparative study of various fatty acids as phase change material to enhance the freshwater productivity of solar still. J Storage Mater 2022;48:103947.

[196] Al-Hamadani AAF, Shukla SK. Water distillation using solar energy system with lauric acid as storage medium. International Journal of Energy Engineering 2011;1:1–8.

[197] Chauhan VK, Shukla SK. Performance analysis of Prism shaped solar still using Black phosphorus quantum dot material and Lauric acid in composite climate: An experimental investigation. Sol Energy 2023;253:85–99.

[198] Pandey N, Naresh Y. Experimental study on the synergistic effects of phase change material, fins, and ultrasonic fogger in a pyramidal solar still. J Storage Mater 2024;98:112997.

[199] Rao R, Sankar KU, Sambaiah K, Lokesh BR. Differential scanning calorimetric studies on structured lipids from coconut oil triglycerides containing stearic acid. Eur Food Res Technol 2001;212:334–43.

[200] Sharma A, Shukla A, Chen CR, Wu TN. Development of phase change materials (PCMs) for low temperature energy storage applications. Sustainable Energy Technol Assess 2014;7:17–21.

[201] Abed QA, Hachim DM. Enhancing the productivity of tubular solar still by using the phase change material. Arab J Sci Eng 2021;46:11645–60.

[202] Kumar M, Yadav C, Manchanda H. Thermal Performance of a Weir-Type Cascade Solar Still: an Experimental Study. International Journal of Advance Research and Innovation 2016;4:335–42.

[203] Toosi SSA, Goshayeshi HR, Heris SZ. Experimental investigation of stepped solar still with phase change material and external condenser. J Storage Mater 2021;40:102681.

[204] Soong YY, Goh HJ, Henry CJK. The influence of saturated fatty acids on complex index and in vitro digestibility of rice starch. Int J Food Sci Nutr 2013;64:641–7.

[205] Sharma RK, Ganesan P, Tyagi VV, Mahlia TMI. Accelerated thermal cycle and chemical stability testing of polyethylene glycol (PEG) 6000 for solar thermal energy storage. Sol Energy Mater Sol Cells 2016;147:235–9.

[206] Al-Hamadani AA, Shukla SK. Experimental investigation and thermodynamic performance analysis of a solar distillation System with PCM storage: energy and exergy analysis. Distributed Generation and Alternative Energy Journal 2014;29:7–24.

[207] Gupta S, Solanki SC. Enhancing the performance of double-slope solar still using nano-enhanced eutectic phase change materials and steel wool fibre as wick material. J Braz Soc Mech Sci Eng 2024;46:274.

[208] Loften JR, Linn JG, Drackley JK, Jenkins TC, Soderholm CG, Kertz AF. Invited review: palmitic and stearic acid metabolism in lactating dairy cows. J Dairy Sci 2014;97:4661–74.

[209] Kateshia J, Lakhera VJ. Analysis of solar still integrated with phase change material and pin fins as absorbing material. J Storage Mater 2021;35:102292.

[210] Kateshia J, Lakhera VJ. Productivity forecasting of the solar still with phase change material using LSTM and GRU neural networks. Eng Res Express 2024;6:045531.

[211] Agrawal R, Singh KDP. Performance evaluation of double slope solar still augmented with binary eutectic phase change material and steel wool fibre. Sustainable Energy Technol Assess 2021;48:101597.

[212] Bisu DY, Aondiyila K, Adama L. Experimental study on the effects of beeswax as absorber for solar still. African Journal of Environmental Sciences and Renewable Energy 2024;16:172–82.

[213] Chang Z, Wang K, Wu X, Lei G, Wang Q, Liu H, et al. Review on the preparation and performance of paraffin-based phase change microcapsules for heat storage. J Storage Mater 2022;46:103840.

[214] Xu Y, Sun T, Guo J, Liu G, Nie X, Liu X. Aggregation behaviour of paraffin molecules with different branched distributions during crude oil gelling: A molecular dynamics study. J Mol Struct 2025;1320:139501.

[215] Liu Y, Zheng R, Li J. High latent heat phase change materials (PCMs) with low melting temperature for thermal management and storage of electronic devices and power batteries: Critical review. Renew Sustain Energy Rev 2022;168:112783.

[216] Lingayat A, Das P, Gilago MC, Chandramohan VP. A detailed assessment of paraffin waxed thermal energy storage medium for solar dryers. Sol Energy 2023;261:14–27.

[217] Prabhu B, Arasu AV, Gurusamy P, Singh AAMM, Arunkumar T. Solar photovoltaic cooling using Paraffin phase change material: Comprehensive assessment. Renew Sustain Energy Rev 2024;197:114372.

[218] Sathyamurthy R, Nagarajan PK, Vijayakumar D, Jawahar MK. Phase change material on augmentation of fresh water production using pyramid solar still. International Journal of Renewable Energy Development 2013;2:115–20.

[219] 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 Procedia 2014;61:2224–8.

[220] Shalaby SM, El-Bialy E, El-Sebaii AA. An experimental investigation of a v-corrugated absorber single-basin solar still using PCM. Desalination 2016;398:247–55.

[221] Sonker VK, Chakraborty JP, Sarkar A, Singh RK. Solar distillation using three different phase change materials stored in a copper cylinder. Energy Rep 2019;5:1532–42.

[222] Kumar TRS, 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.

[223] 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 Storage Mater 2020;31:101610.

[224] 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.

[225] Mohammed AH, Attalla M, Shmroukh AN. Performance enhancement of single-slope solar still using phase change materials. Environ Sci Pollut Res 2021;28:17098–108.

[226] Radomska E, Mika Ł, Sztekler K, Kalawa W, Lis Ł, Pielichowska K, et al. Experimental and Theoretical Investigation of Single-Slope Passive Solar Still with Phase-Change Materials. Energies 2023;16:1188.

[227] Prasad AR, Harshith V, Harish R, Venkatesh I, Prakash MA, Ravishankar S. Investigating single sloped (SSl) and square pyramid (SPy) solar stills using phase changing material (PCM). Mater Today Proc 2023. https://doi.org/10.1016/j.matpr.2023.08.334.

[228] Hafs H, Ansari O, Bah A. Impact of wind-driven mixed convection on the performance of passive solar desalination with PCM heat storage in varied Moroccan climates. Ecological Frontiers 2024;44:73–83.

[229] Khalilmoghadam P, Kiyaee S, Rajabi-Ghahnavieh A, Warsinger DM, Shafii MB. An improved passive solar still integrated with pulsating heat pipes and phase change materials. Sol Energy 2024;275:112612.

[230] 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.

[231] 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.

[232] Aly WI, Tolba MA, Abdelmagied M. Experimental investigation and performance evaluation of an oval tubular solar still with phase change material. Appl Therm Eng 2023;221:119628.

[233] Gowtham M, Chander MS, SailaMallikarujanan KVS, Karthikeyan N. Concentrated Parabolic Solar Distiller with latent heat storage capacity. International Journal of Chemical Engineering and Applications 2011;2:185.

[234] Gowtham M, Neiel KR, Nagarajan V, ChristhuDass P, Thimothy A. Integrated performance analysis of latent heat storage and finned type solar distiller. International Journal of Engineering and Technology 2012;4:613.

[235] Kabeel AE, Abdelgaied M, Mahgoub M. The performance of a modified solar still using hot air injection and PCM. Desalination 2016;379:102–7.

[236] Chaichan MT, Abaas KI, Kazem HA. Design and assessment of solar concentrator distillating system using phase change materials (PCM) suitable for desertic weathers. Desalin Water Treat 2016;57:14897–907.

[237] Bady M, Attia MEH, Kabeel AE, Elazab MA. Enhancing conical solar still performance using high conductive hollow cylindrical copper fins embedded by PCM. Sol Energy 2024;282:112990.

[238] Ahmed MEAE, Abdo S, Abdelrahman MA, Gaheen OA. Finned-encapsulated PCM pyramid solar still - Experimental study with economic analysis. J Storage Mater 2023;73:108908.

[239] Abdelgaied M, Khaira AM, Amro MI, Sharshir SW, El-Samadony MOA. 3E analysis of enhancing solar distillation performance through innovative wick convex stepped absorber, PCM, and evacuated tube solar water collector: Experimental investigation. J Storage Mater 2024;95:112595.

[240] 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 Storage Mater 2022;55:105462.

[241] Abdel-Aziz EA, Mansour TM, Dawood MMK, Ismail TM, Ramzy K. Exergoeconomic and enviroeconomic evaluations of conventional solar still using PCM and electric heater powered by solar energy: an experimental study. Environ Sci Pollut Res 2023;30:66135–56.

[242] Hemmatian A, Kargarsharifabad H, Esfahlani AA, Rahbar N, Shoeibi S. Improving solar still performance with heat pipe/pulsating heat pipe evacuated tube solar collectors and PCM: An experimental and environmental analysis. Sol Energy 2024;269:112371.

[243] Negi A, Verma RP, Saxena A, Ranakoti L, Bhandari P, Singh T, et al. Design and performance of black painted Khes wick modified solar still: An experimental and 5E analysis. International Journal of Thermofluids 2023;20:100491.

[244] Nian YL, Huo YK, Cheng WL. Study on annual performance of the solar still using shape-stabilized phase change materials with economic analysis. Sol Energy Mater Sol Cells 2021;230:111263.

[245] Vigneswaran VS, Kumar PG, Sakthivadivel D, Balaji K, Meikandan M, Dinakar BV, et al. Energy, Exergy, and Economic analysis of low thermal conductivity basin solar still integrated with Phase Change Material for energy storage. J Storage Mater 2021;34:102194.

[246] 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 Res 2021;28:45985–6006.

[247] 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.

[248] Dumka P, Gajula K, Sharma K, Mishra DR, Chauhan R, Siddiqui MIH, et al. A case study on single basin solar still augmented with wax filled metallic cylinders. Case Stud Therm Eng 2024;61:104847.

[249] Mahala T, Sharma N. Experimental investigations of a novel solar still with heat storage materials-energy, exergy, economic and environmental analyses. Desalination 2024;578:117467.

[250] Alqsair UF. Enhancement the production of trays solar still via nano phase change material and preheating feed-water. Case Stud Therm Eng 2024;53:103822.

[251] Suraparaju SK, Samykano M, Dhivagar R, Natarajan SK, Ghazali MF. Synergizing environmental and technological advances: Discarded transmission oil and paraffin wax as a phase change material for energy storage in solar distillation as a step towards sustainability. J Storage Mater 2024;85:111046.

[252] Krishnan AR, Kavitha D. Influence of heat absorber materials sand, soil and paraffin wax in solar still on sustainable water distillation. Case Stud Chem Environ Eng 2023;8:100365.

[253] El-Sebaey MS, Ganaoui ME. Investigating the economic, energetic and exergetic aspects of semi-cylindrical solar still integrated with stepped-basins and phase change material. Process Saf Environ Prot 2024;192:1455–66.

[254] Mustafa MS, Mousa MG, Dawood MMK, Mansour TM, Nabil T. Energy, exergy, economic and environmental analysis of single slope solar still system using phase change material. Results Eng 2024;24:103108.

[255] 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.

[256] 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.

[257] Hassan H, Yousef MS. An assessment of energy, exergy and CO_2 emissions of a solar desalination system under hot climate conditions. Process Saf Environ Prot 2021;145:157–71.

[258] Abo-Elfadl S, Yousef MS, Hassan H. Energy, exergy, economic and environmental assessment of using different passive condenser designs of solar distiller. Process Saf Environ Prot 2021;148:302–12.

[259] 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.

[260] 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.

[261] 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.

[262] Shatar NM, Sabri MFM, Salleh MFM, Ani MH. Energy, exergy, economic, environmental analysis for solar still using partially coated condensing cover with thermoelectric cover cooling. J Clean Prod 2023;387:135833.

[263] Zhang H, Wang W, Fu T, Fang G. Fabrication and thermal properties of novel myristic acid/MgO/BN composite phase change materials for thermal energy storage. J Mater Res 2023;38:3151–9.

[264] Gu X, Liu P, Bian L, He H. Enhanced thermal conductivity of palmitic acid/mullite phase change composite with graphite powder for thermal energy storage. Renew Energy 2019;138:833–41.

[265] Yan Q, Ma G, Wang W. Study of the corrosion of stainless steel with fatty acid/paraffin/graphite composite phase change materials. J Phys Conf Ser 2021;2076:012037.

[266] Pan Y, Fei H, He Q, Wang L, Liang X, Zhou J. Characteristics and properties of myristic acid-stearic acid based ternary composite phase change materials for thermal energy storage. ChemistrySelect 2022;7:e202202390.

[267] Park E-J, Lee AY, Park S, Kim J-H, Cho M-H. Multiple pathways are involved in palmitic acid-induced toxicity. Food Chem Toxicol 2014;67:26–34.

[268] Najjar A, AlMallahi MN, Elgendi M. Evaluating the effect of external and internal condensers on the productivity of solar stills: A review. Energy Convers Manage: X 2024;24:100763.

[269] Zarei M, Rashidi S, Rafee R, Li G. Effects of thermal energy storage and solar water preheater on the performance of cascade solar still - An experimental study. J Storage Mater 2025;112:115520.

[270] 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.

[271] Attia MEH, Harby K, Bedairi BH, Abdelgaied M. Comparative analysis and optimization of different sets of axially magnetized cylindrical magnets to enhance freshwater productivity in hemispherical solar stills, emphasizing 4E performance. Sol Energy Mater Sol Cells 2025;282:113364.

[272] Aftiss R, Najim M, Tbatou T, Hissouf M. Numerical study of conventional solar still integrated dynamic PCM layer. Desalination 2025;600:118493.

[273] Abdel-Aziz MM, Attia MEH. Optimizing conical solar still performance: The impact of broken glass color on distillate yield, energy, exergy efficiency, and economic viability. J Water Process Eng 2025;69:106640.

[274] Surya A, Prakash R, Nallusamy N. Heat transfer and fluid flow characteristics during the charging of a packed bed thermal energy storage unit using myristic acid. J Storage Mater 2025;114:115772.

[275] 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.

[276] 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.

[277] Bacha HB, Abdullah AS, Abdelgaied M. Design and development of a tubular solar distiller using a convex absorber, wick materials, and PCM reservoir combined with a solar parabolic concentrator. J Storage Mater 2023;62:106897.

[278] Alawee WH, Abdullah AS, Mohammed SA, Majdi A, Omara ZM, Younes MM. Testing a single slope solar still with copper heating coil, external condenser, and phase change material. J Storage Mater 2022;56:106030.

[279] Mahala T, Sharma N. Assessing the feasibility of a novel solar still with fins, phase change materials, and wick materials for sustainable water production. Heat Transfer 2024. https://doi.org/10.1002/htj.23266.

[280] 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.

[281] Alsehli M. Improving the performance of a modified solar distiller with phase change material and parabolic trough collector. Environ Sci Pollut Res 2023;30:32710–21.

[282] Elashmawy M, Alhadri M, Ahmed MMZ. Enhancing tubular solar still performance using novel PCM-tubes. Desalination 2021;500:114880.

[283] Alqsair UF, Abdullah AS, Omara ZM, Essa FA. Enhanced solar still operation using a copper coil heat exchanger and phase change material integration. J Storage Mater 2025;113:115557.

[284] Singh VK, Kumar D. An experimental investigation and thermo-economic performance analysis of solar desalination system by using nano-enhanced PCM. Mater Today Sustainability 2024;27:100884.

[285] 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.

[286] 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 Storage Mater 2022;51:104448.

[287] 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 Storage Mater 2022;55:105647.

[288] Anika UA, Kibria MG, Kanka SD, Mohtasim MS, Paul UK, Das BK. Exergy, exergo-economic, environmental and sustainability analysis of pyramid solar still integrated hybrid nano-PCM, black sand, and sponge. Sol Energy 2024;274:112559.

[289] Sharma P, Birla SK. Improving solar still efficiency with nanoparticles – Infused copper cylinders and latent heat storage: An experimental and simulation study. Appl Therm Eng 2024;243:122650.

[290] Pandey N, Naresh Y. A comprehensive 4E (energy, exergy, economic, environmental) analysis of novel pyramid solar still coupled with pulsating heat pipe: An experimental study. Renew Energy 2024;225:120227.

[291] Attia MEH, Harby K, Amin M, Abdelgaied M. Improving the performance of hemispherical solar stills using innovative copper tubes arranged in a honeycomb structure with natural sponges coated with nanoparticles. Appl Therm Eng 2025;269:126130.

[292] Elbar ARA, Baz FB, Marzouk SA, Eldesoukey A, Salem AM. Analyzing solar still performance with PV electricity storage: Energy, exergy, exergoeconomic, and enviroeconomic perspectives. Desalination 2025;597:118400.

[293] Suraparaju SK, Samykano M, Natarajan SK, Rajamony RK, Pandey AK. Waste-derived thermal storage solutions for sustainable solar desalination using discarded engine oil and paraffin wax: A techno-environmental feasibility evaluation. Desalination 2024;576:117318.

[294] Mankai S, Chemkhi S, Madiouli J, Saad FO, Shigidi I, Sghaier J. Performance optimization of solar still employing red-bricks as sensible heat storage material and interfacial evaporation area. Case Stud Therm Eng 2025;66:105798.

[295] Elamy MI, Essa FA, Basem A, Mohammed SA, Alawee WH, Abdullah AS, et al. Novel cylindrical solar still integrated with parabolic solar concentrators, vapor extraction fan, and nano-enhanced phase change material. Desalination 2024;585:117756.

[296] Subramanian K, Meenakshisundaram N, Barmavatu P, Govindarajan B. Experimental investigation on the effect of nano-enhanced phase change materials on the thermal performance of single slope solar still. Desalin Water Treat 2024;319:100416.

[297] Suraparaju SK, Samykano M, Nandavarapu RR, Natarajan SK, Muthuvairavan G, Yadav A, et al. Innovative Double-Finned absorber and Nanoparticle-Enhanced energy storage for enhanced Thermo-Economic performance of solar stills. Sep Purif Technol 2025;361:131360.

[298] Pathak AK, Tyagi VV, Chopra K, Sharma M, Anand S, Kothari R, et al. Energy, exergy, and economic analysis of solar still integrated with phase change material assimilated evacuated tube collector for wastewater treatment. Process Saf Environ Prot 2025;193:1300–19.

[299] Kasaeian A, Nazari NS, Masoumi A, Shabestari ST, Jadidi M, Fereidooni L, et al. A review on phase change materials in different types of solar stills. J Storage Mater 2024;99:113430.

[300] Kumar BS, Varghese J, Jacob J. Optimal thermochemical material selection for a hybrid thermal energy storage system for low temperature applications using multi criteria optimization technique. Mater Sci Energy Technol 2022;5:452–72.

[301] Chandel SS, Agarwal T. Review of current state of research on energy storage, toxicity, health hazards and commercialization of phase changing materials. Renew Sustain Energy Rev 2017;67:581–96.

[302] Zare M, Mikkonen KS. Phase change materials for life science applications. Adv Funct Mater 2023;33:2213455.

[303] Goel V, Dwivedi A, Kumar R, Kumar R, Pandey AK, Chopra K, et al. PCM-assisted energy storage systems for solar-thermal applications: Review of the associated problems and their mitigation strategies. J Storage Mater 2023;69:107912.

[304] Leong KY, Hasbi S, Ahmad KK, Jali NM, Ong HC, Din MM. Thermal properties evaluation of paraffin wax enhanced with carbon nanotubes as latent heat thermal energy storage. J Storage Mater 2022;52:105027.

[305] Kibria MG, Paul UK, Mohtasim MS, Das BK, Mustafi NN. Characterization, optimization, and performance evaluation of PCM with Al_2O_3 and ZnO hybrid nanoparticles for photovoltaic thermal energy storage. Energy Built Environ 2024. https://doi.org/10.1016/j.enbenv.2024.06.001.

[306] Yan S, Feng C, Yuan G, Wang H, Xu H. Preparation and thermal properties of stearic acid-palmitic acid/boron nitride/nanoparticle composite phase change materials. J Storage Mater 2025;114:115853.

[307] Yu Y, Liu Y, Chai H, Tian H, Wu X, Zhao C. Nanoscale insight into the thermal properties of lauric acid and CuO based phase change material used for thermal energy storage. J Mol Liq 2024;393:123630.

[308] Ahmed MMZ, Younes MM, Sharshir SW, Elashmawy M. The latest advances in solar still desalination systems: Analyzing different geometric configurations. Sol Energy Mater Sol Cells 2025;286:113573.

[309] Dinker A, Agarwal M, Agarwal GD. Experimental assessment on thermal storage performance of beeswax in a helical tube embedded storage unit. Appl Therm Eng 2017;111:358–68.

[310] Kamrani P, Hedrick J, Marks JG, Zaenglein AL. Petroleum jelly: A comprehensive review of its history, uses, and safety. J Am Acad Dermatol 2024;90:807–13.

[311] Ameena M, Arumugham M, Ramalingam K, Shanmugam R. Biomedical applications of lauric acid: A narrative review. Cureus 2024;16:e62770.

[312] Bangar SP, Whiteside WS, Chowdhury A, Ilyas RA, Siroha AK. Recent advancements in functionality, properties, and applications of starch modification with stearic acid: A review. Int J Biol Macromol 2024;280:135782.

[313] Liu Y, Jin Y, Chu Z, Osei PO, Wang Y, Wu X, et al. Improved properties of potato starch/myristic acid composite films via high hydrostatic pressure: The role of pressure-induced intermolecular interaction. Food Hydrocoll 2024;154:110120.

[314] Burdock GA, Carabin IG. Safety assessment of myristic acid as a food ingredient. Food Chem Toxicol 2007;45:517–29.

[315] Pascual G, Domínguez D, Elosúa-Bayes M, Beckedorff F, Laudanna C, Bigas C, et al. Dietary palmitic acid promotes a prometastatic memory via Schwann cells. Nature 2021;599:485–90.