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Exploring potential of paraffin wax: A phase change material for improving yield of solar still

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Abstract

The necessity of providing fresh water to the existing population has remained a significant challenge, highlighting the utmost necessity of a sustainable water purification technique. Therefore, the present review article investigates the recent developments in paraffin wax-based enhancements for solar stills for improving freshwater yield. Paraffin wax, a widely used phase change material (PCM), offers high latent heat storage and chemical stability; however, its low thermal conductivity and long-term reliability present significant challenges. Therefore, this article aims to provide sufficient knowledge on the most practical designs of solar still with paraffin wax. Also, the review highlights design modifications, placement strategies, nanoparticle incorporation, and external attachments like heat exchangers and collectors that have been employed to enhance distillate yield. Economic analyses indicate that paraffin-enhanced systems offer lower water production costs compared to conventional solar stills. Challenges such as phase segregation, volumetric expansion, and material degradation over repeated cycles are discussed. This review aims to provide a comprehensive understanding of optimizing solar still performance using paraffin wax, supporting future research and practical implementation for sustainable water desalination. The key findings indicate that pyramid-shaped solar stills are the most suitable design and their integration with paraffin wax can significantly improve the distillate yield by 100 %.

Keywords: Paraffin wax; Latent heat storage; Solar still; Yield improvement; Placement of PCM; Economic analysis

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1. Introduction

Solar distillation has emerged as an efficient technique for desalinating ocean water. Optimal yield is generally achieved when the operating temperature is maintained within the range of 40°C to 80°C [1]. Other techniques, such as reverse osmosis (RO) [2], multi-effect desalination [3], nanofiltration [4], humidification, and dehumidification [5,6], can be employed for ocean water treatment, but these techniques cannot be scaled down for remote regions, which is unviable for the end user.

Nomenclature

AC – annual cost, $
AFC – annual fixed cost, $
AMC – annual maintenance cost, $
ASV – annual salvage value, $
CPL – cost per litre, $
CRF – capital recovery factor
NPBP – net payback period
SFF – sinking fund factor

Abbreviations and Acronyms

CSS – conventional solar still
DSSS – double slope solar still
PCM – phase change material
SSSS – single slope solar still
SBSS – single basin solar still
TESM – thermal energy storage system
TPSS – triangular pyramid solar still
TSS – triangular solar still

Also, the energy supplied to operate these techniques is mainly supplied through thermal power plants that emit a significant amount of CO_2, which is harmful to the environment.

Among the various existing techniques, solar distillation, as shown in Fig. 1, is a promising solution to bridge the gap between accessibility and sustainability, offering a cost-effective, low-maintenance alternative, while significantly mitigating CO_2 through its operational lifespan. The solar distillation technique employs solar still devices to desalinate water, relying on the fundamental principles of evaporation and condensation [7,8]. In this process, initially, impure water is introduced into a basin constructed from high-absorptivity materials such as GI sheet, SS sheet, aluminium, copper, or mild steel [9]. The basin's temperature is elevated as solar radiation passes through a transparent surface, causing an increase in the temperature of the basin's impure water. Subsequently, the impure water undergoes evaporation, transforming into vapour that adheres to the inner surface of the transparent cover. During the condensation process, the evaporated water releases its latent heat by virtue of the temperature gradient between the impure water and the transparent surface (glass). The condensed vapour then drips down and is collected in a container. Later, the water can be used for domestic purposes without compromising taste at an economical cost. Negi et al. [10] reported a cost of $0.01621 per litre of fresh water produced by integrating black painted Khes wick in a single slope solar still (SSSS). Based on the results, it is evident that the water obtained using a solar still is more economical than the packaged water. Additionally, the study claims yearly carbon mitigation of 2.01 tons and 0.25 tons based on energy and exergy studies.

Solar stills are classified as passive solar stills and active solar stills. Passive solar stills are the primary design, also termed as conventional solar still (CSS), reaching a maximum efficiency of 34.3% with a total yield of 3.22kg/m^2/day [11]. Despite their several advantages, literature quoted the low distillate yield as the biggest disadvantage of the solar still. Hence, literature [12] has recommended solar stills for small families. According to [13], the yield of the solar still depends on the temperature difference between the basin water and the inner glass surface. Therefore, several studies have been conducted to enhance the yield of the CSS through internal and external modifications. These modifications include external glass cooling [14], the application of glass coatings [15], the use of wicks [16], thermal energy storage materials [17], encapsulated PCM [7], concentrator [18], as well as the integration of fins [19], reflectors [20], and design alterations [20,52]. Additionally, it has been observed that further enhancements, such as coupling the system with flat plate collectors (FPC) [16], evacuated tube collectors (ETC) [22] and heat pipes (HP) [23], are highly recommended.

Thermal energy storage materials (TESMs), especially phase change materials (PCMs), are considered due to adequate phase transition temperature, high latent storage capacity, adequate thermal conductivity and specific heat [24,25]. Their thermal energy is stored in the form of sensible heat and latent heat, during storage and release, as can be seen in Fig. 2. High latent heat enthalpy results in a significant energy storage capacity, making it ideal for a wide range of applications. The high latent heat mechanism allows paraffin wax to store a significant amount of energy in a relatively small volume, making it an attractive modification to be incorporated in solar stills. PCMs are frequently placed beneath the basin water to absorb thermal energy during peak load hours and maintain the water temperature suitable for evaporation by liberating heat. PCMs have demonstrated their

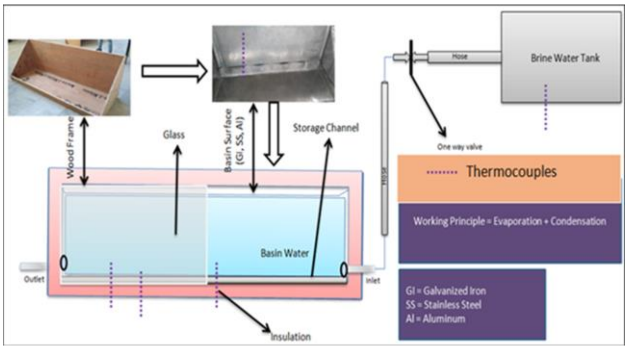

Fig.1. Schematic diagram of solar distillation.

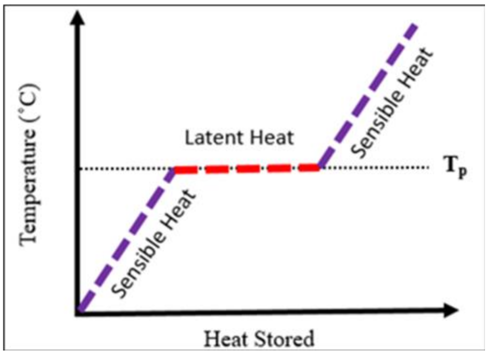

Fig. 2. Energy stored by latent heat storage system (phase change materials).

potential in desalination. According to the literature, myristic acid, palmitic acid, stearic acid, lauric acid, paraffin wax, A39, A42, A48, A55, A58, A62, petroleum jelly, soy wax, bees wax and sheep fat are among the various PCMs, which are already being used in solar stills for improving yield. The corresponding values of the mentioned properties for various PCMs have been discussed by Negi et al. [26]. Moreover, the study reports paraffin wax PCM as an ideal candidate due to the heat storage capacity of approximately 350 kJ/kg, the highest among the reviewed PCMs.

Furthermore, literature [27] has recommended paraffin wax and bees wax for solar distillation application by utilizing a proper MCDM (Multi-Criteria Decision Making) model. In the study, 18 PCMs were investigated based on 7 criteria, including thermo-physical properties, cost, toxicity and compatibility with the container material. The melting temperature, specific heat and thermal conductivity of the few PCMs are illustrated in Fig. 3. The figure suggests that paraffin wax has the highest melting point, followed by stearic acid, A48 PCM and CaCl2.6H2O PCM. However, the least thermal conductivity has been observed for paraffin and A48 PCM, while the highest was observed for inorganic PCM, i.e. CaCl2.6H2O. This comparative study enlightens the drawbacks of paraffin wax, which can be improved by incorporating nanoparticles [28].

Several reviews are available on the application of PCMs in solar distillation, especially paraffin wax. But, its practicality for real-world application is still lacking, and it is an important aspect to evaluate before application in solar stills. Therefore, this study aims to provide the ongoing recent advancement in paraffin wax-based solar distillation. As a result of this review, the best design, climatic and operational parameters related to paraffin wax use will be considered by summarizing recent literature. The article is divided into five sections: Section 1 introduces the background of the study. Section 2 explores the potential of paraffin wax in solar stills. Section 3 examines the effect of paraffin wax placement on solar still performance, and Section 4 discusses the economic feasibility of a paraffin wax-enhanced solar still. Section 5 addresses the challenges and limitations associated with its application, and Section 6 summarizes the conclusions and proposes future research directions.

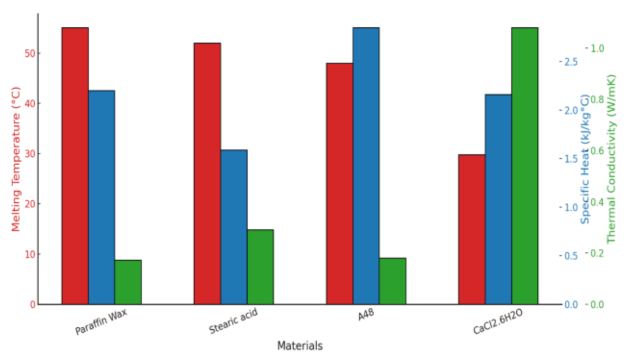

Fig. 3. Thermo-physical properties of a recently used PCMs in solar still [28].

2. Paraffin wax incorporated solar still

The effect of a design modification is crucial for improving solar still yield. For instance, an investigation on a triangular solar still (TSS) with paraffin wax was evaluated and the reported results were later compared with conventional solar still (CSS) to observe the feasibility of the modified solar still (MSS).

Figure 4 shows the improvement reported by the various authors using paraffin wax and other modifications in the solar still. Ravishankara et al. [29] reported a noticeable improvement in freshwater yield by 20%. Additionally, the authors claimed that incorporating paraffin wax led to a higher yield at night as compared to day. Moreover, Sathyamurthy et al. [30] tested paraffin wax on a triangular pyramid solar still (TPSS) under the ambient conditions of South India. They reported a 35% improvement compared to CSS with 20 kg water mass and paraffin wax, suggesting water mass as an important parameter to be considered while designing a solar still.

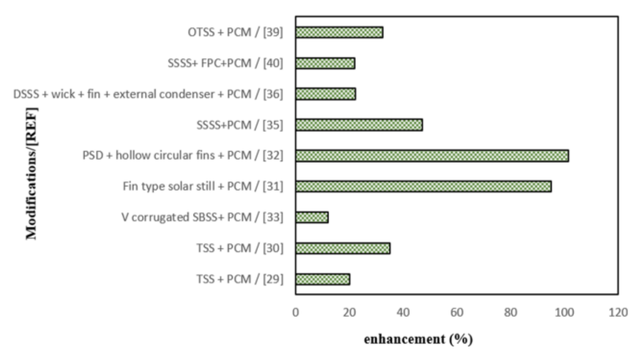

Fig. 4. Distillate yield enhancement for PCM-incorporated solar stills reported by various authors.

The heat transfer has a significant importance when considering a solar still. Therefore, fins are utilized to improve heat transfer through increased surface area, resulting in improved evaporation rate and, consequently, higher yield. Work [55] reported a significant reduction in charging and discharging rate of PCM by 22% and 42%, respectively, for orthogonal fin orientation compared to circumferential fin and no fin configurations. However, the selection of the design of the fins may be a deciding factor and yet needs thorough attention for upcoming studies. In the recent study [31], square hollow fins and paraffin wax improved distillate yield by 95%. Also, the night productivity could be improved by twice as much as a conventional one. Additionally, the effect of a circular hollow fin on a pyramid solar still (PSS) with paraffin wax was investigated by Kabeel et al. [32]. The modified solar still (MSS) significantly improved the yield by 101.5% compared to conventional systems. It was also concluded from the study that the PCM acts as a thermal barrier, which helps to minimize loss from the sides and bottom.

It is obvious to optimize the PCM mass for better yield. So, with a similar perspective, in [33] authors employed paraffin wax in different quantities (18 – 25kg) on the V-shaped corrugated basin surface of the single basin solar still (SBSS). It can be observed from the study that a higher quantity of paraffin wax increases the yield. Furthermore, the wick placed inside the basin increases the capillary action and reduces evaporation time, leading to higher distillate yield. Additionally, a theoretical study was performed with varying masses of paraffin wax. The results revealed that the mass of PCM is the critical factor in the improvement of the distillate yield [34]. During the study, PCM pouches were heated outside under sunlight and afterwards placed inside the distillation unit. Moreover, an improvement of 47.1% was observed with paraffin wax pouches heated outside and later placed inside the basin. Also, frequent opening of the system while placing the PCM pouches inside the system reduced the water temperature due to heat losses [35]. This can be reduced to a certain level by placing the paraffin wax within the solar still.

As mentioned earlier, the yield of the solar still depends on the basin water and glass temperature. To achieve the maximum water temperature, external modifications such as collectors, heat exchangers, condensers, wick or fin are employed. Tuly et al. [36] earlier reported a 22.33% improvement in the yield by integrating fins, condenser, cotton wick and paraffin with a double slope solar still (DSSS). Meanwhile, they observed a trend in the heat transfer shift of the PCM. Kateker et al. [37] reviewed various PCMs, including organic and inorganic PCMs, in a solar still. They recommended paraffin wax and copper oxide nanoparticles for improvement in distillate yield. However, their study fails to determine the optimal placement of the PCM within the solar still. Furthermore, literature [38] has mentioned the significance of reducing the glass cover temperature. Aly et al. [39] reduced glass temperature by employing a sprinkler attachment, while paraffin wax was used for increasing the water temperature of the MSS. The water depth during the experiments varied at different water depths from 0.5 – 2 cm. The best output was reported for the lowest water depth, with an improvement of 32.42% compared to CSS. Apart from this, Table 1 tabulates various parameters that were considered during experimental research on the solar stills.

3. Placement of paraffin wax on the solar still

Paraffin wax PCM is frequently used by researchers, owing to its adequate thermo-physical properties, chemical stability, low cost and low toxicity. Despite this, placement of a PCM in solar distillation is a crucial step that needs to be optimized according to design, weather, and operational conditions, before its implication. For instance, Banoqitah et al. [41] placed paraffin wax beneath the stepped solar still with and without nanoparticles. Additionally, an adaptive neuro-fuzzy inference system (ANFIS) and a hybrid adaptive neuro-fuzzy inference system-particle swarm optimizer (PSO) model were utilized to predict the yield of the solar still. The distillate yield was significantly improved by 66.8% with PCM, while 101.2 % improvement was reported with nPCM compared to CSS.

Furthermore, Tan et al. [42] studied the effect of paraffin wax and petroleum jelly on the yield of the solar still. The PCM was placed beneath the basin water in a separate container. The paraffin wax improved the distillate yield by certain values compared to CSS, resulting in achieving 12.17% efficiency, while 6.36% was reported for CSS. Apart from this, utilizing paraffin wax with external attachments is a fruitful modification. Dawood et al. [43] performed an experimental study by integrating paraffin wax with the SSSS. In their study, they modified SSSS with evacuated tube collectors (ETC) filled with paraffin wax, a parabolic trough collector (PTC), and a serpentine heat exchanger. The system was capable of purifying 11.1 L/m^2/day of potable water while achieving the highest system efficiency of 34% at the flow rate of 0.5 L/min.

It is evident that paraffin wax has low thermal conductivity. Its utility can be improved by incorporating nanoparticles or using paraffin wax with an active solar still. For instance, Alqsair et al. [44] investigated the effect of a parabolic solar concentrator, paraffin wax and silver (Ag) nanoparticle-based paraffin wax on an active drum solar still. The PCM was placed inside the aluminium drum of the solar still. The study optimized the speed of the rotating drum, with 0.3 rpm reported as the optimal

Table 1. Summary of the relevant studies for solar still with incorporated paraffin wax.

Type of solar still	Location	Angle of inclination	Basin material	Basin area	PCM	Modification	Enhancement, %
Triangular [29]	Chennai	-	GI	-	Paraffin	TSS + PCM	20
Triangular [30]	Chennai	-	GI	-	Paraffin	TSS + PCM	35
Single basin [33]	Egypt	30	Copper	-	Paraffin wax	V-corrugated SBSS+ PCM	12
Single slope [31]	India	12	Galvanized Sheet	0.5 m^3	Paraffin wax	Fin type solar still + PCM	95
Pyramid [32]	Egypt	-	Galvanized Steel	0.64 m^2	Paraffin wax	PSD + hollow circular fins + PCM	101.4
Single slope [35]	Poland	30	Stainless-steel	0.5 m^2	Paraffin wax	SSSS+PCM	47.1
Double slope [36]	Bangladesh	25	GI	0.5 m^2	Paraffin	DSSS + wick + fin + external condenser + PCM	22.33
Single slope [40]	India	17	GI sheet	1.5 m^2	Paraffin wax	SSSS+ FPC+PCM	22
Oval tubular [39]	-	-	Stainless-steel	0.24 m^2	Paraffin wax	OTSS + PCM	32.42

Table 2. Parameters evaluated for economic analysis of paraffin wax incorporated solar still [47–51].

Equations	Economic parameter	Formula
(1)	Annual fixed cost (AFC)	AFC = CRF × Initial Investment
(2)	Capital recovery factor (CRF)	$\mathrm{CRF} = \frac{(\mathrm{i}(1+\mathrm{i})^{\mathrm{n}}}{((1+\mathrm{i})^{\mathrm{n}}-1}$
(3)	Annual maintenance cost (AMC)	AMC = 0.15 × AFC
(4)	Annual salvage value (ASV)	ASV = S × SFF
(5)	Sinking fund factor (SFF)	$\mathrm{SFF} = \frac{i}{(1+i)^{n}-1}$
(6)	Annual cost (AC)	AC = AFC + AMC - ASV
(7)	Cost per L of distillate yield (CPL)	$\mathrm{CPL} = \frac{\text{Annual Cost}}{\text{Total Anual Yield}}$
(8)	Net payback period (NPBP)	$\mathrm{NPBP} = \frac{ln\left[\frac{\mathrm{CF}}{\mathrm{CF}-(\mathrm{AFC}\times \mathrm{i})}\right]}{\ln(1+i)}$

Note: i = interest rate, S = salvage value, N = useful life span, CF = (selling price of 1 liter water * annual yield of the solar still)

speed. The nPCM-based solar still showed a 310% improvement in the yield, while achieving a thermal efficiency of 70.5%. Moreover, the authors observed a significant improvement in the evaporation rate with the use of a parabolic solar collector, which was identified as the driving force behind the enhanced yield. Additionally, the authors reported a significant reduction in losses due to the placement of PCM.

4. Economic, energy and exergy analysis of paraffin wax enhanced solar still

An economic study is an important criterion in assessing the viability of implementing a solar still system. The relevant parameters for evaluation are summarized in Table 2. The annual fixed cost (AFC) of the system can be determined using Eq. (1), where the capital recovery factor (CRF) is calculated as per Eq. (2). In this context, ‘i’ represents the annual interest rate, while ‘n’ denotes the expected useful lifespan of the solar still.

Furthermore, initial investment and annual maintenance are essential to ensure the efficient and reliable operation of the system. The maintenance cost is typically estimated at 15% of the fixed cost, as calculated using Eq. (3). Upon completion of the system's useful life, a salvage value equivalent to 20% of the initial investment is considered, which can be evaluated using Eq. (4). The sinking fund factor (SFF), necessary for long-term financial planning, is computed using Eq. (5). The total annual cost (AC) of operating the system is a key parameter in the economic assessment and can be estimated from Eq. (6). At last, the cost per litre (CPL) of the purified water produced is determined using Eq. (7), providing a direct measure of the system’s economic performance. Finally, the net payback period, an essential indicator of investment recovery, is calculated using Eq. (8).

In this context, Suraparaju et al. [45] reported a cost of $0.0246 per litre for a single basin solar still (SBSS) modified with a pin-finned absorber and paraffin wax, compared to $0.026 per litre for a conventional solar still (CSS). Concurrently, Kabeel et al. [46] investigated the impact of incorporating composite materials and paraffin wax, which resulted in a substantial reduction in the cost of distillate yield, reporting a CPL as low as $0.00189 per litre.

The feasibility of the modified system can be ensured by calculating the energy and exergy efficiency. In this context, Suraparaju et al. [52] reported $0.0084 CPL for CSS incorporated paraffin wax. Apart from this, the modified system achieves 26.51% and 2.58% of average energy and exergy efficiency. Moreover, Methre et al. [53] obtained 30.42%, 4.93% and 4.17 L/day of daily average energy efficiency, exergy efficiency and overall yield, respectively. In their study, the thermo-physical properties of the PCM were optimized by varying the Al_2O_3 nanoparticles concentration. Apparently, external attachments are much more beneficial when considering exergy and energy efficiency of the system. For instance, the energy and exergy efficiency in heat pump-assisted solar stills were improved by 65% and 82.3%, respectively, compared to CSS [54].

5. Challenges and limitation associated with paraffin wax for solar distillation application

The past discussions are notably significant, highlighting paraffin wax as a commonly used PCM in the solar still due to its adequate heat storage capacity. However, primary challenges, such as low thermal conductivity, limit its effectiveness during phase transition, resulting in reduced heat transfer rate. Slow heat transfer reduces the availability of stored energy during off-sunshine hours, which ultimately affects the yield of the solar still. Despite the heat transfer limitations, paraffin wax also faces challenges related to its long-term reliability. It has been stated in a past study that its performance deteriorates over repeated thermal cycles. Apparently, phase segregation and volumetric expansion during the melting and solidification process are also a significant concerns to be discussed as they can lead to leakage, encapsulation failures, and reduced latent heat storage capacity over time. These limitations necessitate further research into thermal conductivity enhancement techniques, such as the incorporation of nanoparticles to ensure the long-term stability and viability of paraffin wax in solar distillation applications. Meanwhile, eutectic PCMs are yet to be fully explored as they may offer a solution to the low thermal conductivity of PCM without compromising its other thermo-physical properties.

6. Conclusions and recommendation

Solar distillation systems have attracted significant research interest due to their versatility and ease of use. The current review study focuses on: (1) paraffin wax (PCM) and its role in solar distillation (2) placement of PCM in solar still, (3) the cost analysis.

a) Paraffin wax is preferred for solar applications due to its high latent heat storage capacity and chemical stability. Paraffin wax remains the most widely used PCM owing to its availability, wide operating temperature range, and non-corrosive behaviour.
b) The use of paraffin wax inside the basin of the solar still is often mentioned in the literature. An improvement of 47.1% was observed for the case with paraffin wax pouches heated outside and later placed inside the basin. However, losses associated with the time of opening of the solar still are to be considered.
c) One key challenge observed in traditional solar stills is the frequent opening of the system to add or adjust paraffin wax, leading to temperature losses and reduced efficiency. This issue can be mitigated by placing paraffin wax within the solar still, effectively reducing heat loss and maintaining a more stable water temperature throughout the distillation process.
d) To optimize solar still performance, the choice of storage container material plays a significant role. Copper, stainless steel, and aluminium are all viable options for storing paraffin wax, with each offering advantages in terms of thermal conductivity and durability.
e) Copper and aluminium have excellent thermal conductivity and could enhance the heat retention capacity of paraffin wax, improving the overall distillation rate.
f) Future studies could focus on optimizing the placement of paraffin wax within the still to improve heat transfer efficiency and overall water yield.

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