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A Comprehensive Review of Solar Water Distillation Systems Enhanced with Phase Change Materials (PCMs)

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Abstract Freshwater scarcity is a pressing global issue, especially in arid and semi-arid regions. Solar water distillation presents a sustainable and environmentally friendly solution, albeit limited by low productivity. This paper provides an extensive study on typical solar water distillation systems integrated with PCMs, including system configurations and PCM types as well as thermal performance and engineering application issues. Challenges and prospects of PCM integrated solar still have also been addressed.

Keywords: Solar distillation, Phase change materials, Thermal storage, Water purification, PCM-enhanced solar still

I. INTRODUCTION

Market-based trade, population growth and industrialisation brought on by climate change are increasing the global demand for fresh water. It is the process of solar water distillation to get clean drinking water which mimics the natural hydrological cycle—————. But the single slope solar still modest productivity efficiency and its poor level of production during periods of low sunshine intensity/night cycle. In order to improve the thermal efficiency and productivity of these systems, researchers have been developed some design options such as phase change materials (PCMs).

One way to do this is with a new category of materials that can trap, or store latent heat through phase change, so that solar energy can be collected and used for off-sunligh-t heating. This property of PCMs make them good material for enhanced solar water desalination, where an increase and consistent cyclical variation over the time period as per insolation is observed in the temperature. Utilization of PCMs as thermal storage material in solar still designs also enhanced daily water production and heat retention have been shown (Karima & Islam, 2020; Zhang et al., 2021).

II. LITERATURE REVIEW

Literature review related to passive solar stills with different configurations and performance characteristics launched by Durkaieswaran and Murugavel (2015), paved a good path for further research dealing with PCM integration. Karima and Islam (2020) designed a cost-effective tubular solar still which indicated towards enhanced thermal retention as well as productivity. Zhang et al. Stuart et al., on thermally localized passive desalination with high efficiency, potentially preparing innovations such as PCMs used in Stokes et al. for energy storage (2021).
Alwan et al. experimented modifications such as solar collectors and reflectors immensely [7] (2020) and Abdullah et al. (2021), with scaling due to higher heat input resulting in improved water output. Mosleh et al. (2015) and Shafii et al. It also applied vacant tube as well as parabolic trough collectors in hybrid systems which showed boost in efficiency when thermal storage element i.e. PCMs are introduced (Wang et al. 2016).
Notably, Nwosu et al. One such study by Mayank et al. (2021) investigated post-sunset production from a single-slope double-effect solar still with PCM in the form of paraffin wax, along these lines yielding an extra incentive for the distillation application. Also, Chaichan and Kazem (2015) illustrated a solar water heater yielding highly enhanced process productivity using PCM. Safaei et al. (2019) and Rufuss et al. Additionally, in (2017) an nano-enhanced PCM was used to further increase thermal conductivity and thereby reduce system response time.
Studies by Prakash et al. (2021), El-Sebaey et al. El-Sebaii (2005) also established that the performance of solar stills is dependent on water depth and geometric configuration, which just as well emphasizes the need for optimized PCM positioning and system design (2022). Reviews by Bazri et al. (2018) and Hawlader et al. A separate simulation study by

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Lund (2003) also found that wrapping finned storage or encapsulating latent heat systems in an insulated material increased their thermal capacity. [36]
In general, the literature suggests that PCM integration – with enhanced design features (e.g., reflectors, collectors or nanoparticle additives) – consistently improves thermal storage and water yield in solar still systems.

III. CLASSIFICATION OF SOLAR STILLS INTEGRATED WITH PCMS

3.1. Single-Slope Basin Stills with PCM
It is the most widely used configuration for its simplicity and constructability. The PCM, a paraffin wax or salt hydrates are placed below the basin liner or encapsulated in small metal / polymeric storage devices. This stored heat then slowly resumes after sunset, extending the evaporation cycle to maximise total exposure. Research by Nwosu et al. When compared to the studies by Hassani et al.(2021) and Chaichan and Kazem(2015) improvements in daily water production with paraffin-based PCMs are substantial

3.2. Multi-Effect and Cascade-Type Stills
These complex designs use numerous evaporative and condensative sections, with one being on top of the other or in a cascade configuration. In such designs, the accomplished temperature gradient between stages are stabilized by means of PCMs which consequently improves heat reutilization and overall productivity. In the studies like Mosleh et al. (2015) and Shafii et al. In their studies, Yao et al. (2016) showed that PCMs maintain inter-stage thermal continuity and this can result in a better desalination performance.

3.3. Solar Still Hybrids with Collectors and PCM
This one involves solar collectors like flat plate, parabolic trough collectors linking to the still for preheating of basin water or PCM. This synergy leads to elevated basin temperatures and, thus improved PCM charging especially when solar radiation is low (even during cloudy weather) Figure 6 Results of Alwan et al's experiments. (2020), Abdullah et al. (2021), and Safaei et al. (2019) also highlight substantial increases in efficiency and water yield with hybrid setups compared to conventional systems.

IV. TYPES AND CHARACTERISTICS OF PCMS USED

4.1. Organic PCMs
PCMs based on organic compounds (e.g. paraffin waxes, fatty acids) are widely used for solar distillation applications due to their non-corrosivity, chemical stability, possibility of simple recycling, and safety aboard as well. Paraffin wax is among the most common as it has a consistent melting temperature and it is abundant, thus very affordable. However, the low thermal conductivity of those organic PCMs can be a limitation and may delay heat absorption and release. Performance for researchers is typically boosted by concapsulation or through metal fins or conductive additives.

4.2. Inorganic PCMs
Inorganic phase-change materials (PCMs) mostly being hydrated salts stand out due to the high latent heat storage capacity and improved thermal conductivity as compared to organic PCMs. These features of excellence primarily endear them to systems which have to exchange heat quickly. There is however the problem of phase segregation, super cooling and chemical corrosiveness of these compounds. These shortcomings can be mitigated by a special encapsulation technology, dosing of additives, or by adding stabilizing agents. In spite of these shortcomings, they are highly thermally competent and thus inorganic PCMs can be used in high-efficiency distillation systems.

4.3. Nano-Enhanced PCMs
Table 1: Comparative Properties of PCM Types

PCM Type	Example	Latent Heat (kJ/kg)	Thermal Conductivity (W/m·K)	Advantages	Limitations
Organic PCM	Paraffin Wax	200–250	~0.2	Stable, non-toxic, cheap	Low thermal conductivity
Inorganic PCM	Hydrated Salts	250–350	~0.5	High energy density	Supercooling, corrosiveness
Nano-Enhanced PCM	Paraffin + Al_2O_3	210–260	~0.5–1.2	Improved heat transfer	Cost, nanoparticle dispersion issue

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Thermal conductivity of conventional phase change materials (PCMs) is usually poor. If this is the case, to overcome such a drawback, nano-enhanced PCMs (NEPCMs) based on PCMs with nanoparticles like aluminium oxide (Al_2O_3), copper oxide (CuO) and graphene oxide were proposed. The addition of such nanoparticles significantly increases the thermal conductivity, enhances the speed of heat travel, improves the energy storing and releasing processes. Based on empirical studies conducted by Safaei et al. (2019) and Rufuss et al. (2017), the thermal performance of solar stills is considerably increased, and the production of fresh water is raised by using NEPCMs.

V. PERFORMANCE METRICS AND COMPARATIVE STUDIES

The evaluation of solar stills with phase-change materials (PCMs) focuses on quantitative parameters like water production, thermal performance and a cost-effectiveness level.

- **Yield Improvement:** Empirical research posit that on introducing PCMs, the freshwater production involving daily production can increase by 20 50 percent. Nwosu et al. (2021) and Chaichan and Kazem (2015) state, respectively, longer operating hours and increased yields in the evenings.
- **Efficiency**: The thermal efficiency is enhanced since the PCMs trap heat, and release when the sun is not shining. Systems using new-generation PCMs (NEPCMs) have other benefits, which is due to better heat-transfer properties.
- **Cost-Effectiveness:** The total economics are positive, even though encapsulation and PCM materials would prove expensive initially, with the benefit of achieving increased yield and fewer working hours. In a specific case, life-cycle analysis often prefers PCM-based solar distillation where remote or off-grid applications are needed.

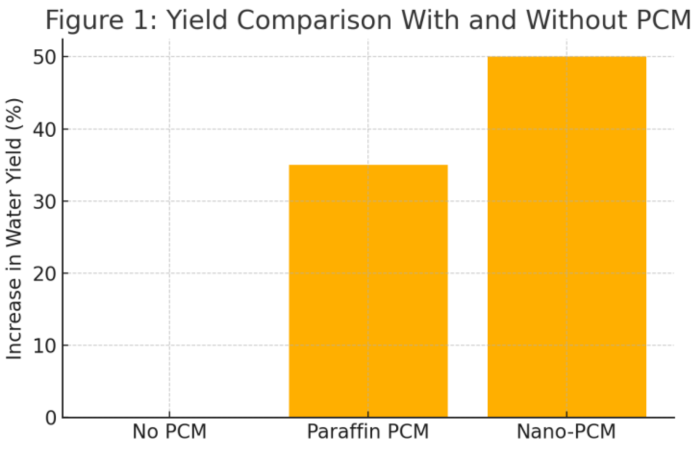

Figure 1: Yield Comparison with and Without PCM

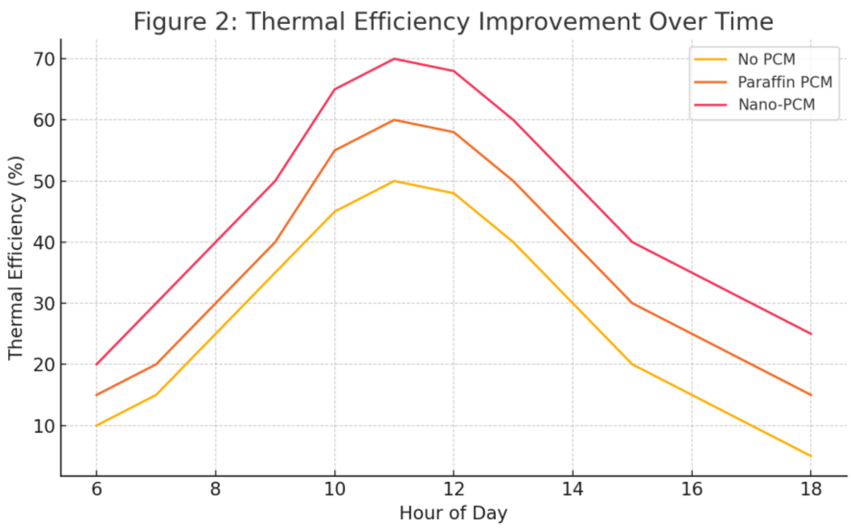

Figure 2: Thermal Efficiency Improvement Over Time

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VI. CHALLENGES AND LIMITATIONS

Table 2: Key Challenges in PCM-Based Solar Still Design

Challenge	Description	Mitigation Strategy
Low thermal conductivity	Slow charging/discharging rate of heat	Use of nanoparticles or fins
Leakage and degradation	Loss of material or reduced performance over time	Advanced encapsulation or composite PCMs
Environmental disposal	Synthetic PCMs may not degrade easily	Research into biodegradable PCM alternatives

Despite their advantages, the use of PCMs in solar distillation systems presents several challenges:

- Low Thermal Conductivity: Common PCMs like paraffin wax have poor thermal conductivity, which can delay heat exchange.
- Leakage and Degradation: Over multiple thermal cycles, some PCMs may leak or chemically degrade, reducing system longevity and performance.
- Encapsulation Complexity: Proper encapsulation is essential to prevent leakage, improve heat transfer, and enhance mechanical strength. However, it adds complexity and cost.
- Environmental Impact: Disposal of synthetic PCMs after end-of-life use can pose environmental risks unless biodegradable or recyclable materials are employed.

VII. FUTURE DIRECTIONS

Future research and development efforts should focus on the following areas:

- Low-Cost, High-Performance PCMs: Research into naturally available or bio-derived PCMs could offer sustainable and economical alternatives.
- Bio-Based and Recyclable PCMs: Innovations in green chemistry can lead to environmentally friendly thermal storage materials.
- Advanced Encapsulation: Micro- and nano-encapsulation technologies using conductive shells or smart coatings can improve durability and thermal performance.
- Hybrid PV/T Systems: Integrating photovoltaic/thermal (PV/T) units with solar stills and PCMs could maximize solar energy utilization by generating electricity and heat simultaneously.

VIII. CONCLUSION

Integrating PCMs into solar water distillation systems presents a promising avenue for enhancing freshwater production, especially in resource-limited settings. The ability of PCMs to store and release thermal energy aligns well with the intermittent nature of solar radiation. Despite material and integration challenges, the consistent gains in yield and efficiency across various experimental setups underscore the transformative potential of PCMs. Continued research into sustainable PCM materials, advanced encapsulation methods, and hybrid system designs could propel PCM-based solar distillation into a mainstream, sustainable water purification solution.

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