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Advances in Encapsulated phase change materials for Enhancing solar water systems: Current Progress and Future Directions

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Abstract

This review thoroughly evaluates recent advancements in micro- and nano-encapsulated phase change materials (M/N-ePCMs), which are critical for enhancing the thermal efficiency and reliability of solar water systems. It focuses on various encapsulation methods—physical, chemical, hybrid, and scalable industrial techniques—that improve thermal conductivity, latent heat storage, and environmental resilience. The integration of ePCMs in solar water heaters, stills, ponds, and tanks is examined, highlighting their ability to stabilise output temperatures, extend operational periods, and optimise thermal storage under fluctuating solar conditions. Through a detailed analysis of experimental and numerical studies, the review offers insights into design strategies, material compatibility, and system-level enhancements enabled by ePCMs. It also addresses challenges such as cyclic stability, cost-effectiveness, and large-scale implementation, providing recommendations for future research. This work serves as a key resource for developing energy-efficient, sustainable solar water systems using M/N-ePCM technologies.

Keywords: PCMs, solar water systems, solar stills, solar water heaters, heat transfer enhancement, renewable energy.

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1. Introduction

Solar energy systems are crucial in the shift toward renewable and sustainable energy sources, offering a clean alternative to traditional fossil fuels [1]. Despite their potential, the intermittent nature of solar radiation presents a challenge in maintaining consistent energy output. To address this issue, advanced materials are being explored to enhance the efficiency and performance of solar systems. Encapsulated phase change materials (ePCMs) have emerged as a promising solution, as they can effectively manage heat flow and improve system performance [2]. The encapsulation process enhances the stability and functionality of PCMs, making them more suitable for use in solar applications by preventing issues such as leakage and degradation, while also boosting heat transfer efficiency [3]. However, direct use of PCMs is hindered by challenges like leakage, corrosion, and instability. These issues can be addressed by encapsulating PCMs within protective shells, which may take forms such as cylindrical, rectangular, or spherical shapes. The practice of encapsulation, originating in the 19th century [4], involves enclosing PCMs in a protective material to increase surface area, thereby boosting heat transfer features and efficiency, but also isolating the PCM from its environment. This insulation is particularly critical in sensitive applications, such as food storage and blood transportation, where preventing contact with surroundings is essential for safety and efficacy [5].

Micro- and nanoencapsulated PCMs (M/N ePCMs) have become integral to solar energy systems, finding widespread use in applications such as thermal energy storage [6-9], photovoltaic (PV) cooling [10-12], solar water heating systems [13], and solar thermal collectors [14, 15]. In thermal energy storage, ePCMs effectively capture and release latent heat to address the intermittent nature of solar radiation, ensuring a steady energy supply. These materials have revolutionised the efficiency, reliability, and thermal management of solar water systems, including solar water heaters, still distillation units, and pasteurisation systems. By storing and releasing substantial latent heat, ePCMs optimise the use of variable solar energy and extend system operation beyond daylight hours. They also improve temperature stability, minimise thermal losses, and enhance stratification in water tanks, promoting effective thermal layering and prolonged heat retention. In solar stills, ePCMs boost freshwater production by sustaining high basin temperatures after sunset. Additionally, the small size and high energy density of ePCMs allow seamless integration into system components without significantly increasing volume or weight, making them ideal for compact, portable, or off-grid solar water applications.

In solar water heating systems, M/NPCMs are integrated into storage tanks or collector units to absorb surplus thermal energy during peak irradiance and release it during periods of low or no sunlight [16]. This thermal regulation ensures a more stable and continuous supply of hot water, especially beneficial in residential and off-grid applications [13]. Encapsulation at the micro or nano scale enhances the thermal conductivity, dispersibility, and stability of PCMs, resulting in quicker heat response and longer operational life. In solar still distillation systems, micro- and nano-encapsulated phase change materials (M/N-ePCMs) are utilised to sustain high basin temperatures after sunset, enhancing the evaporation-condensation cycle and increasing freshwater production. These materials mitigate the issue of nighttime temperature drops, which typically lower water yields. Their small particle size promotes uniform heat distribution and rapid phase transitions, ensuring consistent heat release into the basin water during periods without sunlight. In solar pond systems, ePCMs are incorporated into storage zones to maintain temperature stratification and store heat for prolonged periods. This enables solar ponds to supply thermal energy during nighttime or cloudy conditions, improving reliability and extending operational durations. The use of ePCMs also reduces convective heat losses and enhances long-term thermal layering. In solar water tanks, ePCMs are integrated within or around the tanks to boost heat storage capacity and extend heat retention. This is particularly beneficial for domestic solar hot water systems, where consistent temperature maintenance is essential. Research indicates that ePCMs improve energy efficiency and thermal stratification in tanks, enhancing overall system performance and resilience.

This review explores the critical role of M/N-ePCMs in improving the thermal efficiency of solar water systems, focusing on their applications in solar water heaters, stills, ponds, and tanks. It synthesises advancements in material design, encapsulation techniques, and integration methods that enhance system responsiveness, heat retention, and durability. Challenges such as long-term thermal stability, scalability of production, and cost-effectiveness are also discussed. By addressing both technological progress and research gaps, this review provides a forward-looking perspective on how ePCM innovations can advance efficient, sustainable solar water systems, particularly in regions facing water and energy constraints.

2. M/N ePCM

Micro/nano-encapsulated phase change materials (M/N-ePCMs) significantly improve the efficiency and dependability of solar water systems by storing and releasing thermal energy during phase changes [17], enabling precise temperature control, minimising energy losses, and enhancing operational stability. Encapsulation prevents leaks, boosts thermal conductivity, and ensures durability over multiple thermal cycles, making M/N-ePCMs well-suited for integration into solar collectors, storage tanks, and heat exchangers [18-20]. Their compact nature and rapid thermal response make them particularly effective for addressing the variable thermal requirements of solar water heating technologies. Phase change materials (PCMs) are classified into organic, inorganic, and eutectic types, each with unique benefits and encapsulation challenges critical for selecting core materials in micro/nano-encapsulated PCMs (M/N-ePCMs) for solar thermal applications. Organic PCMs, like paraffins and fatty acids, offer chemical stability, non-corrosiveness, and compatibility with polymeric shells, making them suitable for low - to medium-temperature systems, though their low thermal conductivity often requires enhancement via hybrid or nanoparticle techniques. Inorganic PCMs, such as salt hydrates and metallics, provide higher latent heat and thermal conductivity for medium- to high-temperature applications but face issues like supercooling, phase separation, and corrosiveness, necessitating robust encapsulation methods. Eutectic PCMs, comprising organic-organic, inorganic-inorganic, or organic-inorganic mixtures, allow customizable thermal profiles and sharp phase change temperatures, though their stability and congruent melting depend on precise encapsulation control. This classification guides the optimisation of encapsulation strategies to ensure reliable, long-term performance in solar water heating systems.

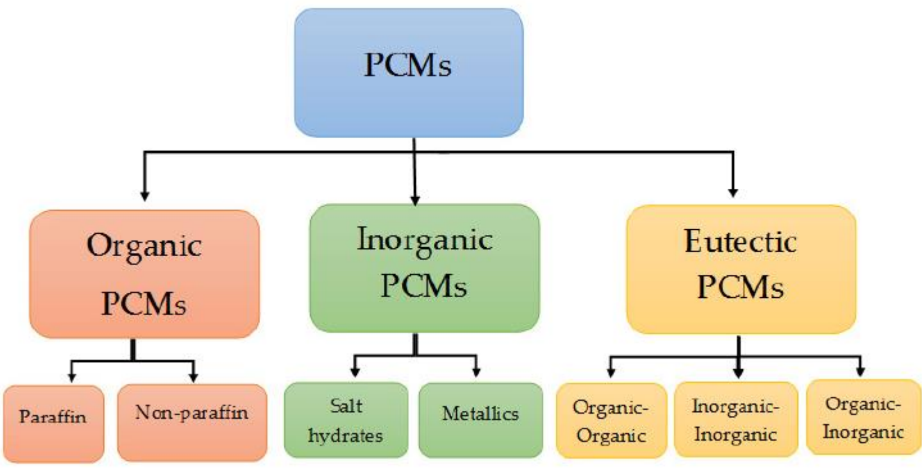

Figure 2. Classification of PCM-based chemical compositions [21].

2.1. Microencapsulation for PCMs

Microencapsulation is a widely adopted technique used to enclose either solid or liquid substances within microscopic containers, effectively isolating them from external environmental conditions. In this process, the encapsulated substance is referred to as the core material, while the protective layer is referred to as the shell. This concept was initially introduced in the 1950s by Green and Schleicher [22], who successfully encapsulated dye materials using gelatin and arabic gum through a coacervation method, leading to the development of carbonless copy paper [23]. Over the decades, microencapsulation has found extensive applications across various industries, including chemical, pharmaceutical, cosmetic, and particularly thermal systems. In the context of thermal energy storage, this method has gained prominence due to its ability to mitigate leakage issues and environmental concerns commonly associated with phase change materials (PCMs) at elevated temperatures. Encapsulation forms a physical barrier that limits direct exposure of PCMs to the surrounding medium, reducing risks of degradation or loss of material. Additionally, microencapsulation enhances heat transfer efficiency and offers structural stability against volume expansion and contraction during repeated phase transitions [8].

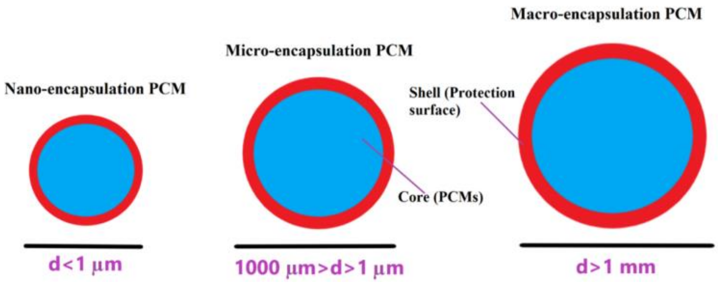

Figure 1. Different size ranges of encapsulated PCMs [5].

In terms of material development, Kawaguchi et al. [24] fabricated a microencapsulated PCM based on a Zn-Al alloy with a 30 wt% Zn core, achieving a phase transition temperature range of 437–512°C and a latent heat of 117 J/g. In another investigation, the same research group developed a medium- to high-temperature PCM incorporating $Al(OH)_3$ via microencapsulation, obtaining a thermal energy storage density of 0.48 GJ/m^3 at a concentration of 1.7 g/L. The encapsulated PCM showed excellent thermal and cyclic stability beyond 100 cycles, a performance improvement attributed to the stabilising effect of Al $(OH)_3$ [25]. Further developments by Yuto et al. [26] focused on creating a microencapsulated PCM with an Al-Ni alloy core containing 5 wt% Ni. After 100 cycles of melting and solidification, the material maintained a shell composed of α-Al_2O_3, which contributed to improved thermal reliability. Addressing the corrosion challenges commonly associated with high-temperature PCMs, Sakai et al. [27] introduced a microencapsulated PCM consisting of 25 wt% Al-Si core enclosed within an Al_2O_3 shell. This material exhibited a heat storage temperature of 577°C and latent heat of 108–122 J/g, Yang et al. [29] utilised in situ polymerisation to prepare a microencapsulated PCM slurry using encapsulation shells made from polystyrene, PMMA, and polyethyl methacrylate. Their analysis via DSC revealed how variations in tetradecane content influenced the latent heat capacity and phase transition temperatures.

2.2. Nano encapsulation PCMs

Significant progress has been made in recent years in the fabrication of optimised nano-scale structures, eliminating previous limitations in the manufacturing sector. This advancement has prompted extensive research into the synthesis of nanoscale phase change materials (PCMs) using nanomaterials and modern fabrication techniques to address the inherent low thermal conductivity of PCMs and enhance heat transfer performance [28]. For example, Fang et al. [29] fabricated nano-encapsulated n-tetradecane (average size ~100 nm) using in-situ polymerisation, with a urea-formaldehyde shell. Their results highlighted the applicability of such nanocapsules in a wide range of thermal energy storage systems. Similarly, Qiu et al. [30] produced nano-encapsulated PCMs by a suspension-like polymerisation method, incorporating 75.3 wt% n-octadecane as the core and methyl methacrylate (MMA) as the shell. Thermal and mechanical characterisations via DSC, TGA, and hardness tests indicated that samples containing pentaerythritol tetraacrylate as a crosslinker showed the highest melting (156.4 J/g) and crystallisation enthalpies (182.8 J/g), along with superior mechanical strength. In another effort, Hu et al. [31] utilised in-situ polymerization to encapsulate paraffin with carboxymethyl cellulose, achieving a peak phase change enthalpy of 83.46 J/g at a paraffin content of 63 wt%.

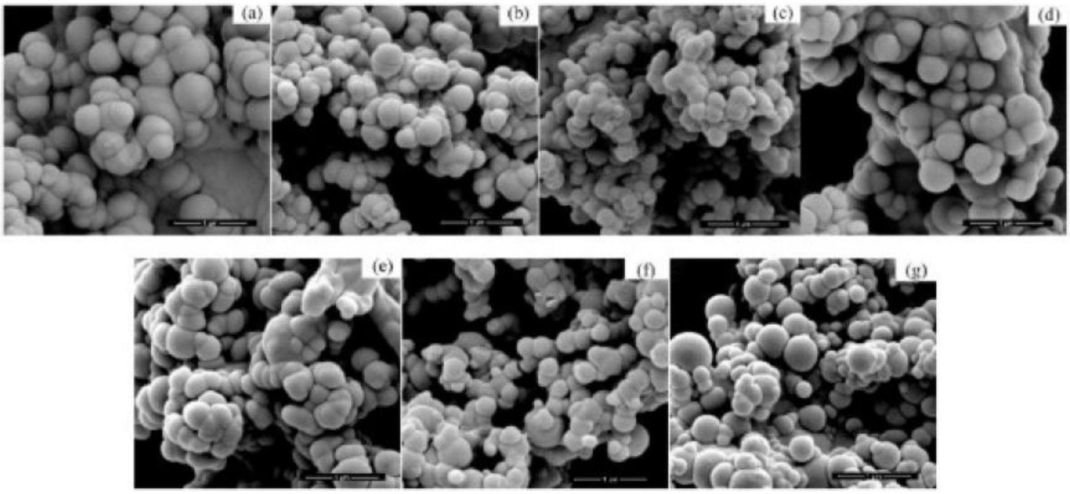

Figure. 2 SEM images of NEPCMs, as reported by Zhang et al. [31], showcasing different average particle sizes: (a) 449.6 nm, (b) 295.5 nm, (c) 261.3 nm, (d) 397.8 nm, (e) 352.3 nm, (f) 295.5 nm, and (g) 339.4 nm [21].

Park et al. [32] fabricated magnetic nano-encapsulated PCMs (Mag-PCM) using paraffin as the core and polyurea as the shell. Additionally, Fang et al. [33] developed cold-temperature-targeted nano-PCMs using n-tetradecane via in situ polymerisation. These materials demonstrated strong durability through 40 freeze-thaw cycles, suggesting suitability for low-temperature thermal applications. Latibari et al. [34] prepared nanocapsules via the sol-gel method with palmitic acid as the core and silica (SiO_2) as the shell, reporting stability across more than 2500 melt-freeze cycles and highlighting their favourable thermal and chemical reliability for energy storage. Chen et al. [35] synthesised nano-capsules with n-dodecanol as the core and PMMA as the shell through mini-emulsion polymerisation. They explored the impact of emulsifiers (DNS-86) and co-emulsifiers (hexadecane), determining that a 2% mass ratio of hexadecane to n-dodecanol yielded the best performance, with a latent heat of 98.8 J/g and 82% encapsulation efficiency. In a related study, Chen et al. [36] encapsulated n-dodecanol using a styrene-butyl acrylate copolymer shell, resulting in an enthalpy of 109.2 J/g and a phase change temperature of 18.4 °C. Further, Fang et al. [37] developed nano-encapsulated PCMs containing n-dotriacontane using mini-emulsion polymerisation. The nanocapsules, averaging 168.2 nm in diameter, underwent extensive structural and thermal assessments using TEM, XRD, DSC, and TGA, confirming their robust performance for energy storage use.

3. Processes and materials for M/N-ePCMs

Encapsulation significantly improves the stability, durability, and heat transfer efficiency of phase change materials (PCMs) tailored for solar water heating applications [5]. M/N-ePCMs refer to micro- or nano-encapsulated PCMs, with or without nanoparticle enhancements. These advanced materials address the limitations of bulk PCMs, such as low thermal conductivity, leakage during phase changes, and reduced cycling stability, by encasing them in protective shells that enhance mechanical and thermal resilience. Encapsulation methods are classified into physical, chemical, hybrid, and industrial-scale techniques, each with distinct benefits in performance, material compatibility, and scalability [38]. The choice of encapsulation method depends on factors like the intended application, thermal cycling needs, capsule size, and the type of PCM or nano-enhanced PCM (NPCM). Physical methods are straightforward and eco-friendly, while chemical methods provide better long-term performance. Hybrid and industrial approaches are gaining traction for their scalability and efficiency in integrating PCMs into practical solar energy systems. This section offers a comprehensive overview of the main encapsulation techniques for M/N-ePCMs, their mechanisms, and their relevance to solar thermal applications. It also explores the materials used for shells and supports, such as polymers, inorganic oxides, and hybrid composites, laying the groundwork for understanding their performance in solar water heating systems.

Figure 3. Categorisation of Preparation Methods for Encapsulated Phase Change Materials [5]

Figure 1 presents a detailed classification of encapsulation techniques for ePCMs and NPCMs, outlining the primary process categories and their associated methods. This visual representation serves as a foundation for the in-depth discussion in the subsequent subsections. This section thoroughly examines the main encapsulation techniques for M/N-ePCMs, detailing their underlying mechanisms and their significance for solar thermal applications. It also explores the materials used for shells and supports, such as polymers, inorganic oxides, and hybrid composites, providing a basis for understanding their performance in solar water heating systems.

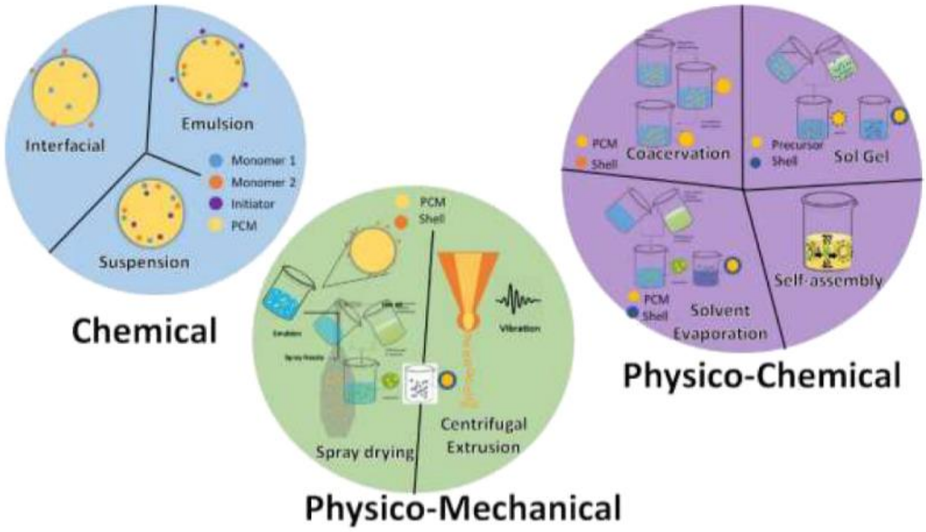

Figure 4. Overview of common encapsulation methods for PCM [39].

Encapsulation of phase change materials (PCMs) can be accomplished through various synthesis methods [40], as illustrated in Fig. 4. These methods focus on achieving uniform particle sizes, mechanical and chemical stability, and a high core-to-shell ratio to maximise energy storage capacity. The approaches are categorised into chemical and physical methods. Chemical methods involve forming microcapsules through chemical reactions. Physical methods include physicochemical techniques, where the shell material retains its original composition without undergoing chemical changes, and physicochemical techniques, which involve both chemical and physical processes to form the shell.

3.1. Physical Techniques

Physical encapsulation entails enclosing phase change material (PCM) within a shell or matrix through non-reactive, mechanical processes. As these methods avoid chemical reactions, they are straightforward and economical. Techniques such as coacervation, ionic gelation, and solution gelling are included in this category [8, 41]. These approaches are particularly suitable for organic PCMs and applications prioritising eco-friendly materials or biopolymer-based shells. Coacervation is a popular method due to its ability to create a uniform coating around PCM droplets through phase separation in colloidal systems [42]. Ionic gelation employs multivalent ions (e.g., Ca^{2+}, Al^{3+}) to cross-link biopolymer molecules, forming a stable gel matrix encasing the PCM [43]. Solution gelling integrates PCM into hydrogels, providing a semi-solid encapsulation environment. Although physical methods are simpler, they may encounter issues like limited mechanical stability or PCM leakage during repeated phase changes, which can restrict their use in high-temperature, long-term solar applications.

Table 1. Summary of Common Physical Encapsulation Methods for M/N-PCM

Method	Shell Materials	PCM Type	Key Mechanism	Advantages	Limitations

Coacervation [44-46]	Gelatin, Gum Arabic, Chitosan	Organic, hydrophobic	Colloidal phase separation around PCM	Simple, cost-effective, uniform coating	Limited thermal stability, potential leakage
Solution Gelling [47-49]	Agar, Alginate, PVA	Hydrophilic, salt hydrates	Gel formation via temperature/pH changes	Biocompatible, eco-friendly	Low thermal conductivity, unsuitable for high temperatures
Ionic Gelation [43, 50-52]	Chitosan + Ca^{2+}/Al^{3+} ions	Organic, biopolymer-based	Ionic cross-linking of shell polymers	Easy to process, no organic solvents needed	Mechanical stability varies with ion strength

Table 1 provides a comparative analysis of three prominent physical encapsulation techniques for micro/nano-encapsulated PCMs (M/N-ePCMs): coacervation, solution gelling, and ionic gelation. These methods utilise non-reactive, physical processes to encapsulate PCMs, making them appealing for eco-friendly and cost-effective applications, particularly in low-to-moderate temperature solar systems. Coacervation is appreciated for its simplicity and ability to create uniform coatings with natural polymers like gelatin and gum Arabic. However, its limited thermal stability and susceptibility to PCM leakage during repeated thermal cycles restrict its suitability for high-demand thermal applications. Solution gelling employs temperature- or pH-responsive polymers to encase PCMs within hydrogel matrices. While this approach is environmentally friendly and biocompatible (ideal for sustainable solar technologies), it is hindered by low thermal conductivity and structural weaknesses at higher temperatures. Ionic gelation offers controlled cross-linking by using divalent or trivalent ions (e.g., Ca^{2+} or Al^{3+}) to stabilise shell materials like chitosan. This method avoids organic solvents and simplifies processing, but its mechanical stability relies on ion concentration and shell uniformity.

3.2. Chemical Techniques

Chemical encapsulation involves forming a polymeric shell around PCM via chemical reactions, such as polymerisation. This category encompasses interfacial polymerisation, in situ polymerisation, emulsion polymerisation, and suspension polymerisation [53]. These techniques produce microcapsules with excellent structural integrity and thermal stability, crucial for the repeated heating and cooling cycles in solar thermal systems. Interfacial polymerisation forms a polymer shell at the boundary of immiscible liquids, effectively encapsulating the PCM core. In-situ polymerisation allows shell formation directly within the reaction medium, providing versatility in capsule size and uniformity. Emulsion and suspension polymerisation excel in creating nano- and micro-sized capsules with improved dispersion and process control. These chemically formed shells offer superior thermal, chemical, and mechanical resistance, making them ideal for solar collectors, storage tanks, and high-performance solar water systems exposed to temperature fluctuations and environmental conditions.

Table 2. Comparison of Microencapsulation Methods for Phase Change Materials (PCMs)

Method	Reaction Type	Shell Material	PCM Compatibility	Advantages	Limitations
Interfacial Polymerisation [54-57]	Interface reaction	PU, PMMA, MF	Organic, hydrophobic	Uniform shell, excellent thermal stability	Sensitive to pH and surfactant levels
In-situ Polymerisation [58-61]	Bulk polymerization	PMMA, PVA, UF	Organic, hydrophilic	Precise capsule size, high encapsulation efficiency	Needs precise temperature and monomer management
Emulsion Polymerisation [62-64]	Free radical in emulsion	PS, PU	Low-melting-point PCMs	Fine capsule dispersion, scalable production	Complex surfactant requirements generate waste
Suspension Polymerisation [65-67]	Thermal/catalytic in suspension	Acrylics, Methacrylate	Organic PCMs, paraffin	Larger capsules, high payload capacity	Less effective for nanocapsules, limited monomer control

Table 2 compares four microencapsulation methods for phase change materials (PCMs), detailing their reaction types, shell materials, PCM compatibility, advantages, and limitations. Interfacial polymerisation [55, 68], using an interface reaction with materials like PU, PMMA, and MF, suits organic and hydrophobic PCMs, offering uniform shells and high thermal stability, but is sensitive to pH and surfactant levels. In-situ polymerisation [58], a bulk polymerisation process with PMMA, PVA, and UF, works with organic and hydrophilic PCMs, providing controlled capsule sizes and efficient encapsulation, though it requires precise temperature and monomer control. Emulsion polymerisation (polymerisation), employing free radical reactions in emulsions with PS and PU, is ideal for low-melting-point PCMs, enabling fine capsule dispersion and scalability, but involves complex surfactant systems and waste generation [64, 69]. Suspension polymerisation, using thermal or catalytic reactions with acrylics and methacrylates, supports organic PCMs and paraffins, producing larger capsules with high payload capacity, yet it is less suitable for nanocapsules and offers limited monomer control. This analysis highlights the trade-offs in shell material selection, encapsulation efficiency, and process complexity for tailored PCM applications [70].

3.3. Hybrid Encapsulation Methods

Hybrid encapsulation integrates physical and chemical techniques to leverage their combined advantages, enhancing thermal conductivity, leakage resistance, and capsule stability. For instance, a PCM may initially be physically coated using spray drying or coacervation, followed by chemical polymerisation to create a durable outer shell [71]. This multi-step process significantly improves durability under cyclic thermal loads. In solar water heating systems, hybrid methods are particularly promising as they enhance both thermal responsiveness and mechanical strength of PCM capsules. Their ability to customise capsule properties makes them well-suited for advanced applications, such as nanoparticle-doped PCMs (NPCMs) and systems requiring long-term thermal reliability. Although more complex, hybrid encapsulation is increasingly emphasised in advanced solar thermal research due to its adaptability to real-world operational demands.

3.4. Industrial and Scalable Encapsulation Methods

Industrial encapsulation techniques prioritise scalability, cost-effectiveness, and commercial viability. These include methods like spray drying [72, 73], solvent evaporation [74], pan coating [75], and centrifugal extrusion [76], designed for high-throughput production and large-scale PCM integration into energy systems. Spray drying atomises PCM solutions into hot air to produce dry, encapsulated particles [72]. Solvent evaporation forms capsules by removing volatile solvents from a PCM–polymer mixture. Pan and air suspension coating involve layering PCM particles with polymers in rotating or fluidised beds, while centrifugal extrusion enables continuous microcapsule formation by co-extruding shell and core materials. These methods are critical for implementing encapsulated PCMs in solar water heaters, storage tanks, and modular thermal panels, where fabrication ease, uniformity, and cost-efficiency are paramount.

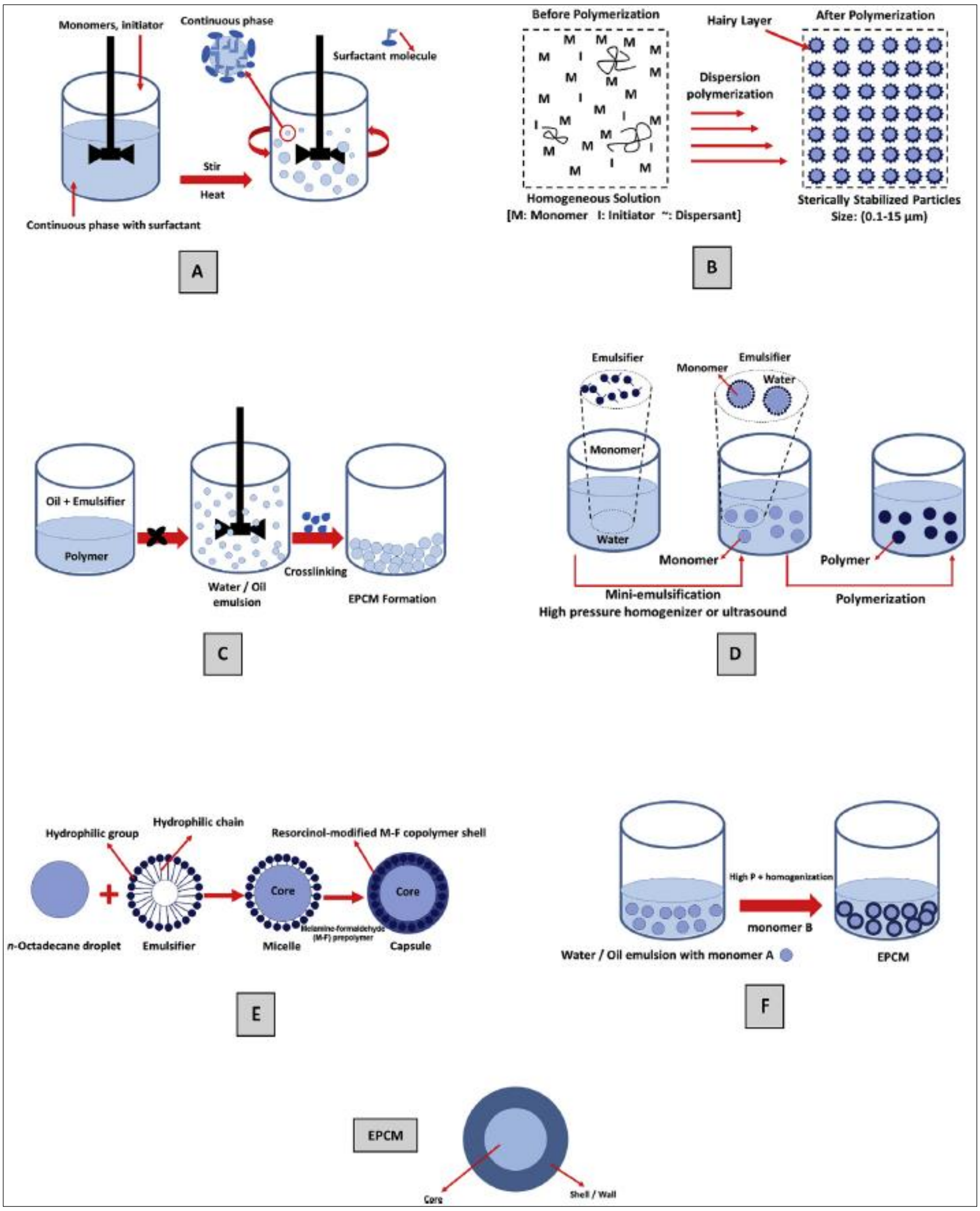

Figure 5. Schematic outline of different chemical polymerisation processes for encapsulating PCMs. (A) Suspension polymerisation; (B) Dispersion polymerisation; (C) Emulsion polymerisation; (D) Mini-emulsion polymerisation; (E) In situ polymerisation; (F) Interfacial polymerisation yielding encapsulated phase change materials (EPCM) [39].

4. Encapsulated PCM application in solar water systems

Encapsulated phase change materials (ePCMs) are used in solar water systems to improve efficiency, energy storage, and operational stability [16, 77-79]. By integrating PCMs with micro- or nano-encapsulation, these materials can be tailored to specific temperature requirements, ensuring consistent performance over multiple thermal cycles [80]. Key applications include solar water heaters [81-83], solar still [84-86], solar pond and agricultural irrigation system, with each type offering unique benefits and challenges. This section examines the role of ePCMs in enhancing solar water heating systems, focusing on their integration, advantages, and limitations.

4.1. Solar water heater

Solar water heaters (SWHs) are widely utilised in residential and industrial settings due to their straightforward design and cost-effectiveness [87]. However, their reliance on solar availability results in temperature variability and reduced heat availability during low-sunlight periods. To mitigate this, phase change materials (PCMs) are increasingly incorporated into SWH systems to capture surplus thermal energy during high solar exposure and release it when sunlight is limited. PCM integration enhances thermal consistency, boosts energy efficiency, and provides a more reliable hot water supply [88]. Numerous recent studies have highlighted the benefits of integrating phase change materials (PCMs) into solar water heaters [87-91]. For example, paraffin wax encapsulated in spherical capsules or flat plates has been employed to improve heat retention and minimise temperature drops during cloudy periods or at night. Additionally, research has investigated nano-enhanced PCMs and finned heat exchangers to enhance thermal conductivity and accelerate discharge rates. This sub-section examines recent progress in integrating PCMs, focusing on emerging trends, system configurations, and performance enhancements. In some studies

Table 3. Summary of Studies on Solar and Heat Pump Water Heaters Integrated with Phase Change Materials (PCM)

Work	SWH Type	PCM Type & Encapsulation Method	Integration Location	Key Findings
Reddy (2007) [92]	ICS-SWH	Paraffin wax with 4, 9, 19 fins	Top enclosure	The 9-fin configuration achieved optimal water temperature and minimised nighttime heat losses.
Chaabane et al. (2013) [93]	ICSSWH	Myristic acid & RT42-graphite	In collector	Reduced nighttime heat losses; myristic acid outperformed other PCMs.
Fazilati & Alemrajabi (2013) [83]	Jacketed SWH	Paraffin in spherical capsules	In tank	Energy storage increased by 39%; hot water delivery extended by 25%.
Huang et al. (2014) [94]	PCM-Floor SWH	Macro-encapsulated capric acid	PCM floor layer	Released 37.7 MJ over 16 hours, improving floor heating efficiency.
Murali et al. (2015) [95]	Thermosyphon SWH	Paraffin wax in an Al cylinder	Top of the storage tank	PCM improved thermal stratification, charging efficiency, and overall performance.
Manimaran & Senthilkumar (2015) [96]	Cascaded SWH	Paraffin wax	Base of the absorber plate	PCM captures heat during daylight, releasing it at night, boosting performance in off-sunshine periods.
Murali & Mayilsamy (2016) [81]	Stratified SWH	Paraffin wax	Top tank (varied inlets)	Bottom inlet with diffuser improves stratification and increases hot water output in discharge mode.
Varghese et al. (2016) [97]	CPC-ICS SWH	None	Drum at CPC focus (no PCM)	Air gaps in CPC arms reduce heat loss by up to 52.5%, achieving a maximum temperature of 53°C and 38% efficiency.
Hamed et al. (2016) [98]	ICS SWH	PCM (varying thickness)	Rectangular cavity	PCM melts faster than it solidifies, enhancing heat storage but lowering nighttime exergy efficiency.
Zou et al. (2017) [99]	HPWH	Water-PCM with fins	HPWH tank	Storage capacity increased by 14%; second run time reduced by 13%; improved COP.
Wu et al. (2018) [100]	SWH + OHP	PCM with oscillating heat pipe	Near collector	PCM reduced CE fluctuations by over 30%, maintaining 50°C at night.
Bouhal et al. (2018) [101]	SWH with PCM modules	Paraffin in spherical capsules	In tank	PCM fully melted in 2.5 hours; the modelling method influenced prediction accuracy.
Kumar & Mylsamy (2019) [102]	All-glass ETCSWH	Paraffin + 1% SiO_2 (NCPCM)	Built-in TES	NCPCM raised morning water temperature to 39.6°C; energy efficiency reached 74.8%.
Sharol et al. (2019) [103]	Cross-matrix absorber	Paraffin wax	Inside the CMA unit	Optimal heat gain at 0.01 kg/s flow rate; lower flow rates yield higher temperatures, ideal for heating/drying.
Dileep et al. (2021) [104]	ETCSWH	Paraffin wax in multiple containers	Inside tubes	More containers accelerated melting; placement significantly affected performance.
Avargani et al. (2021) [88]	Conventional SWH	Paraffin wax, encapsulated	Storage tank	Delivered 1200 L at 60±2°C for 8 hours, ensuring a stable hot water supply.

Saravanan et al. (2023) [105]	Conventional SWH	PCM (unspecified), modelled numerically	In tank	PCM system stored 320% more energy compared to non-PCM systems.
Bharathiraja et al. (2024) [106]	Flat plate SWH	Paraffin wax + MWCNT/SiO_2 (HnPCM)	In collector	Efficiency increased from 64.7% to 71.7%; outlet temperature reached 70°C.
ElCheikh et al. (2024) [107]	Passive SWH	Paraffin wax encapsulated in straight tubes or coils	Inside the storage tank	PCM fully melted in 3 h; discharge raised water temp by 20 °C; thermal efficiency reached 64.5%.
Manikandan et al. (2024) [108]	Domestic SWH	Paraffin wax (50 kg, 60 °C melting point)	Storage tank	System supplied 200 L/day; saved 1168 kWh/year; validated via SAM simulation and experimental testing
Badr et al. (2025) [109]	Solar collector with PCM	Paraffin wax + 2/4 fins	In the shell side of the collector	Fins reduced the melting time by 81%; outlet temperature reached 67.5°C.
Kumar et al. (2025) [110]	Conventional SWH	Paraffin + Cu, SiC, BN nanoparticles	Tank loop	Efficiency improved from 47.6% to 52%; solar fraction increased to 75%.

Table 3 summarises studies on solar water heaters (SWHs) integrated with encapsulated phase change materials (PCMs), highlighting various SWH types, PCM types, encapsulation methods, integration locations, and key performance outcomes. Predominantly featuring flat plate, thermosyphon, and evacuated tube collectors SWHs (ETCSWH), the studies primarily utilise paraffin wax due to its high latent heat and cost-effectiveness, often enhanced with additives like SiO_2, MWCNT, or nanoparticles (e.g., Cu, SiC, BN) to improve thermal conductivity. Encapsulation methods include spherical capsules, finned structures, tubes, and cavities, typically integrated into storage tanks or collectors. Key findings show significant performance enhancements: PCMs increase energy storage up to 320% in Saravanan et al., 2023 [110], extend hot water availability, e.g., 25% longer delivery in Fazilati & Alemrajabi, 2013 [83]. Innovations like fins, reducing melting time by 81% in Badr et al., 2025 [109] and nano-enhanced PCMs, e.g., 74.8% efficiency in Kumar & Mylsamy, 2019 [102] further optimise thermal stability and output temperatures, up to 70°C in Bharathiraja et al., 2024 [106]. The table underscores a trend toward hybrid designs that enhance thermal management across diverse climatic conditions, though variability in efficiency gains and integration methods suggests a need for standardised approaches to maximise scalability and cost-effectiveness.

4.2. Solar still systems

The solar desalination system harnesses solar energy to convert brackish water into potable water [111]. Solar desalination systems are categorised into two types based on their energy input: active and passive [111-113]. In passive systems, solar energy serves as the sole thermal energy source, driving the production of distilled water. Conversely, active systems [114] incorporate additional energy sources, such as electric heaters [90, 91] or heat exchangers [115], to enhance distilled water output alongside solar energy. The integration of encapsulated phase change materials (PCMs) in solar desalination systems improves the evaporation rate during periods of low solar radiation, such as at night, thereby increasing both water production and system efficiency. Kannan et al. [116] investigated the impact of encapsulated PCM and aluminium scraps on the water output of a hemispherical solar desalination system. They tested paraffin wax encapsulated in aluminium scrap cans, arranged in square and triangular configurations, to optimise thermal energy storage. The system featured an evaporation surface area of 0.1963 m² and hemispherical diameters of 0.25 m. Results showed daily freshwater production of approximately 5.63 L/m², 4.88 L/m², and 2.92 L/m² for the square-shaped, triangular-shaped, and conventional systems, respectively. The cost per litre (CPL) was approximately 0.0186 $/L, 0.0128 $/L, and 0.0111 $/L for the square-shaped, triangular-shaped, and conventional systems, respectively. Figure 6 illustrates the experimental setup with encapsulated PCM.

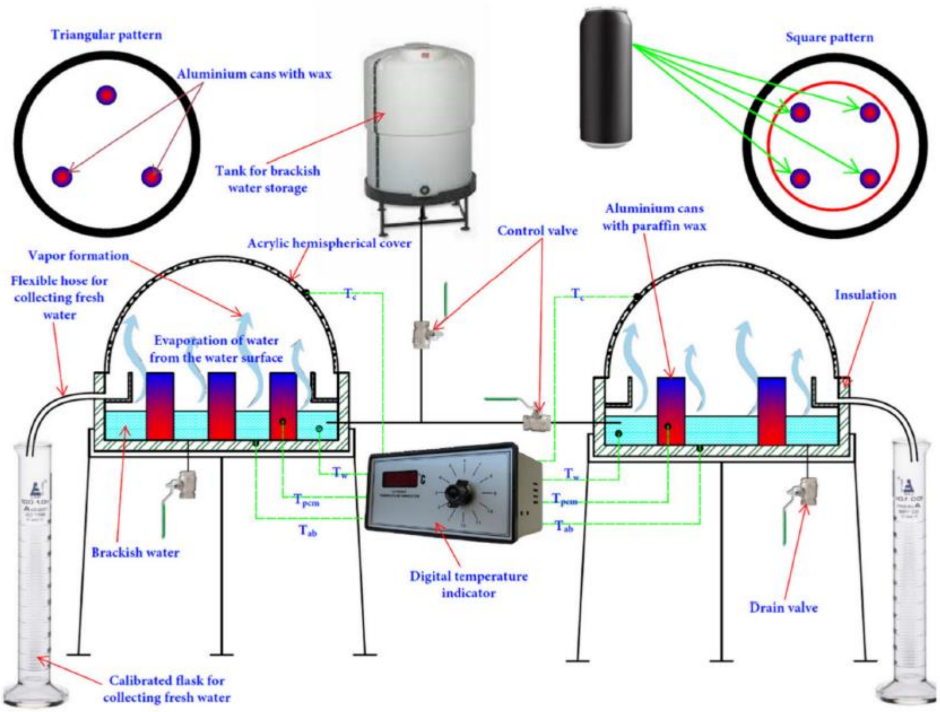

Figure 6. Solar-powered hemispherical desalination with PCM [116]

Arunkumar et al. [117] performed an experimental study comparing single-slope and pyramid solar stills, both equipped with a parabolic concentrator and encapsulated phase change materials (PCM), see Figure 7. The stills featured an evaporation surface area of 0.25 m², a water depth of 0.03 m, and a 0.004 m thick glass cover, optimised for solar transmission. Copper balls filled with PCM served as thermal storage units. Their findings showed daily freshwater outputs of approximately 2680 mL/m² for the single-slope solar still (SSSS), 3240 mL/m² for the pyramid solar still (PSS), 7160 mL/m² for the SSSS with PCM, and 7346 mL/m² for the PSS with PCM, demonstrating the significant advantage of combining PCM with solar concentration technologies.

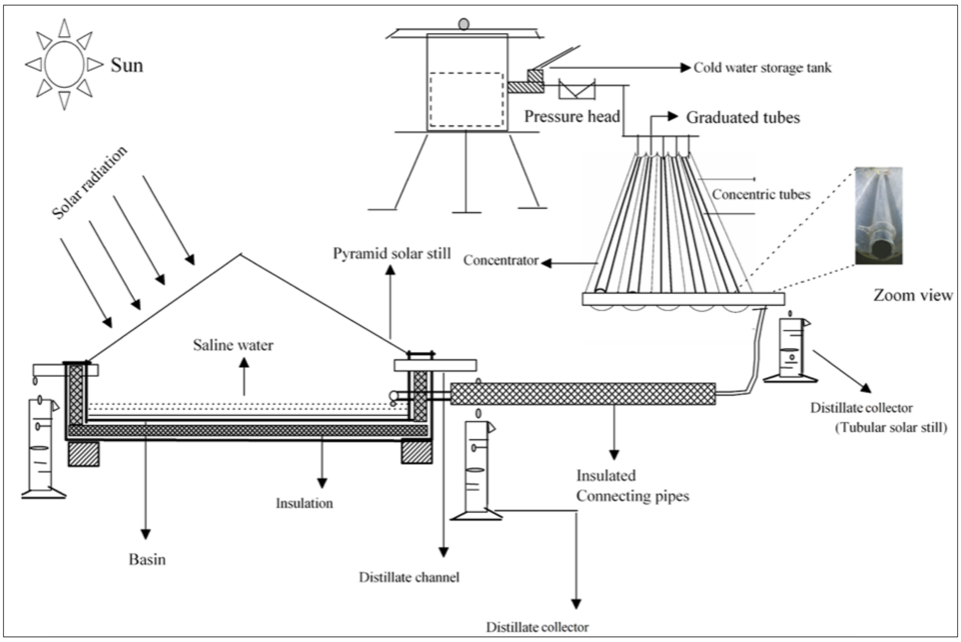

Figure 7. Schematic view of the solar still configuration combining a compound parabolic concentrator with a concentric circular tubular solar still and pyramid solar still (CPC-CCTSS-PSS) [117].

These results are consistent with the patterns observed in Figure 8, which illustrates the hourly productivity variations across different system configurations using Compound Parabolic Concentrator (CPC) and Compound Conical Concentrator (CCC) technologies.

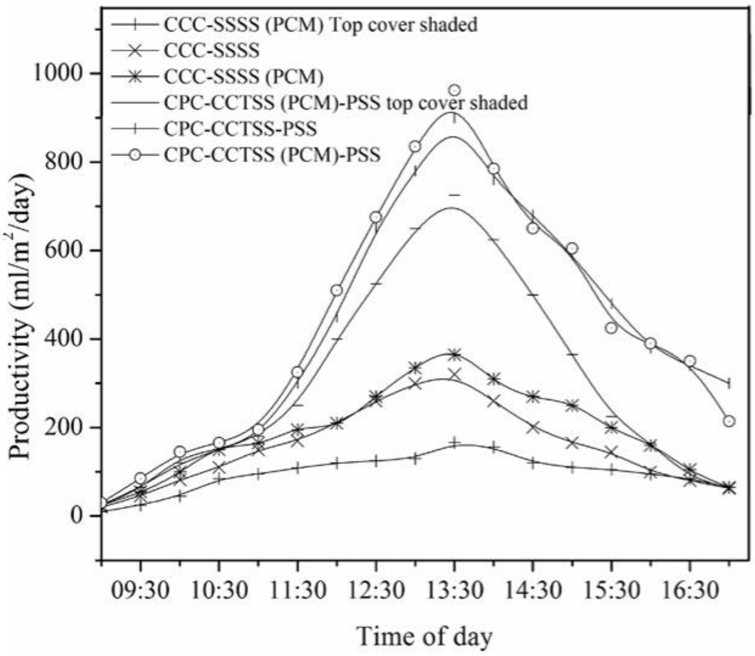

Figure 8. Hourly productivity of solar stills with different configurations, including concentrator types, PCM integration, and top cover shading. The CPC-CCTSS (PCM)-PSS setup showed the highest performance, highlighting the impact of combined enhancements (CCC: Compound Conical Concentrator; CPC: Compound Parabolic Concentrator; SSSS: Single-Slope Solar Still; PSS: Pyramid Solar Still; CCTSS: Concentric Circular Tubular Solar Still) [117].

The evaluated systems include conventional single-slope solar stills (CCC-SSSS), those enhanced with PCM, and advanced setups integrating CPC with a concentric circular tubular solar still (CCTSS) and a pyramid solar still (PSS). Figure 8 shows that the CPC-CCTSS (PCM)-PSS configuration, a highly integrated system, achieved the highest productivity, peaking at over 1000 mL/m²/day around 13:30. This outperforms other setups, such as CCC-SSSS and CCC-SSSS (PCM), which yielded notably lower outputs. Additionally, shading the top cover in some configurations slightly reduced peak productivity but enhanced condensation, highlighting the intricate balance between vapour production and condensation dynamics. This analysis confirms that integrating PCM with solar concentrators (CPC or CCC) significantly enhances distillate yield, particularly when combined with optimised designs like pyramid solar stills and concentric tubular configurations. Such integration improves thermal management, extends evaporation periods, and boosts overall system efficiency, aligning with and building upon the findings of Arunkumar et al. [117].

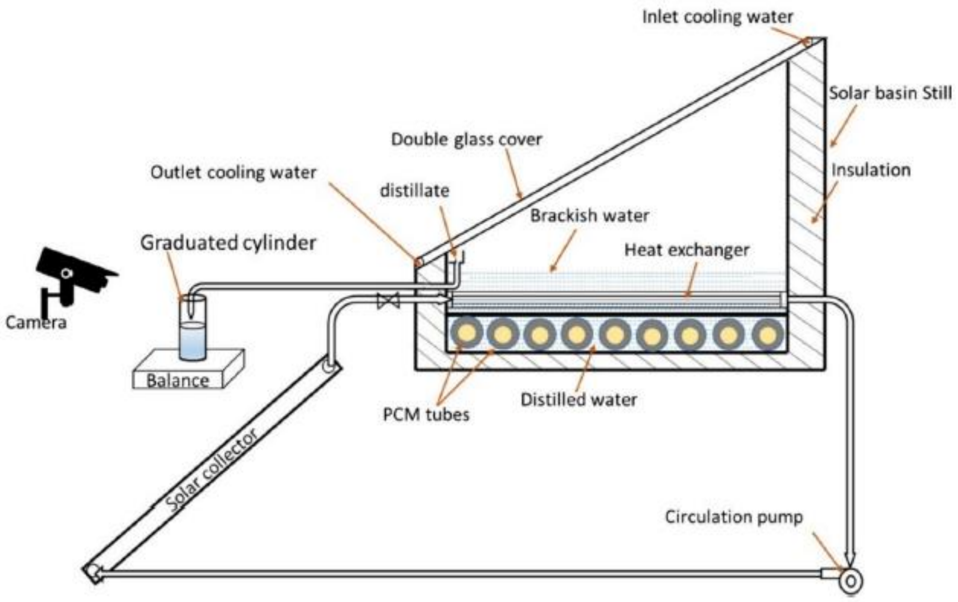

Figure 9. Single-slope solar still with integrated encapsulated PCM and solar collector [84].

Al-harahsheh et al. [84] explored the effects of encapsulated PCM and solar collectors on solar still efficiency, as shown in Figure 9. They used sodium thiosulfate pentahydrate as the PCM due to its high latent heat, minimal volume change during melting, and cost-effectiveness. By storing heat in the encapsulated PCM during the day and releasing it as needed, the system extended its operational time. Water was circulated between the solar still and the solar collector. Their findings revealed that encapsulated PCM at lower water depths significantly increased water production, with a maximum daily output of 4.3 L/m².

Figure 10. Single slope type of solar still integrated with encapsulated-PCM concentric tube ring [118].

Vigneswaran et al. [118] examined the influence of single and multiple PCMs on water production in solar desalination systems, comparing three configurations: conventional solar stills, solar stills with PCM-1, and solar stills with PCM-2, see Figure 10. The system was constructed from a galvanised iron plate with a thickness of 0.0016 m. PCMs were placed in annulus pipes within the water to facilitate heat transfer. The daily water production was approximately 3680 mL/m², 4020 mL/m², and 4400 mL/m² for the conventional, PCM-1, and PCM-2 systems, respectively. The exergy efficiencies were 3.92%, 3.23%, and 3.52% for the respective systems. Figure 18 depicts the solar still with encapsulated PCM.

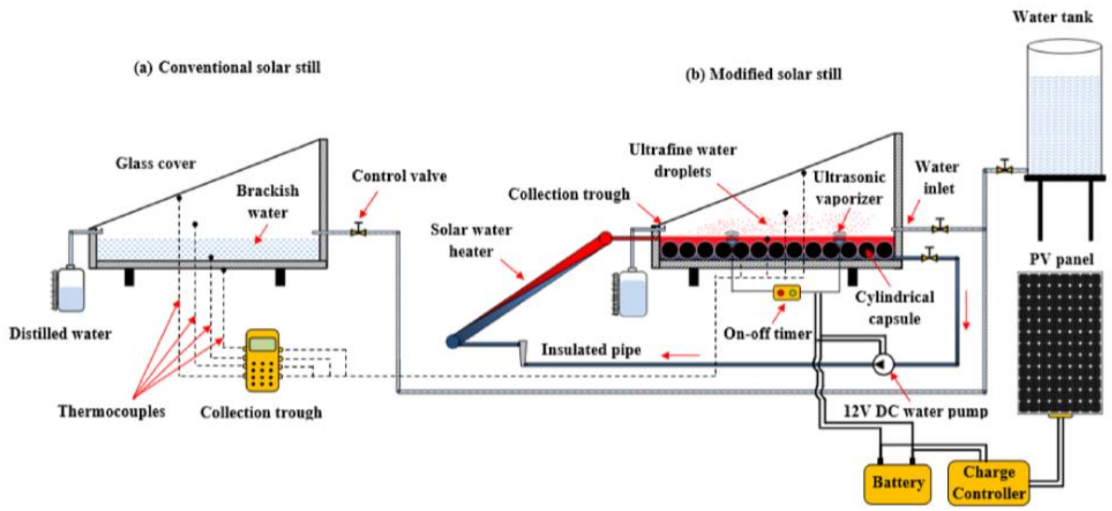

Figure 11. Configuration of (a) conventional solar still and (b) hybrid solar still utilising solar collector, ultrasonic atomiser, and encapsulated PCM [119]

Abed et al. [119] experimentally studied the freshwater output of a solar still incorporating encapsulated PCMs, an ultrasonic atomiser, and a solar collector (**Figure11**). They used twenty cylindrical components (25 cm diameter, 1 m length, 90% filling ratio) filled with paraffin as the PCM. Saline water was circulated between the solar collector and the solar still to enhance the distillation rate. Results showed a 30.6% increase in water production with encapsulated PCM. The highest energy efficiency, 39.3% for a 30-minute operation, was achieved with the ultrasonic atomiser. Figure 12 illustrates the solar still with a solar collector, ultrasonic atomiser, and encapsulated PCM.

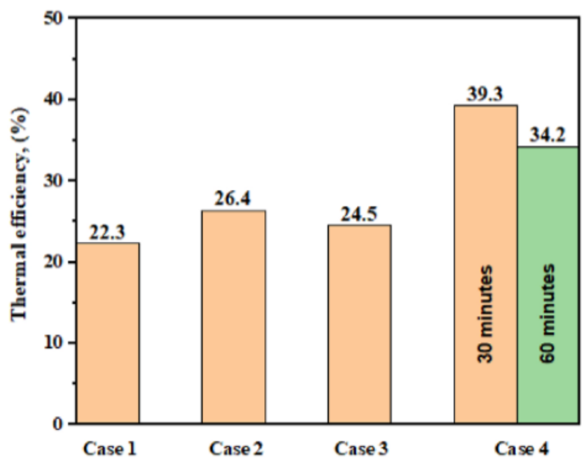

Figure 12. Thermal efficiency of the solar still: Case 1 : CSS; Case 2 : +PCM; Case 3 : +PCM +heater; Case 4 : +PCM +heater +ultrasonic vaporiser [119].

Figure 12 illustrates the average thermal efficiency of the solar still for all tested cases. In Case 4; which includes the conventional solar still enhanced with PCM cylindrical capsules, a solar water heater, and a high-frequency ultrasonic (HFU) vaporiser—the thermal efficiency decreased from 39.3% to 34.2% when the HFU operation time was extended from 30 to 60 minutes. This decline is likely due to increased water vapour accumulation in the water-glass region, which impairs heat transfer and reduces the condensation rate on the glass surface. In Case 3, where only the PCM capsules and solar water heater were used, the solar still achieved higher daily water productivity compared to the conventional setup (Case 1). However, its thermal efficiency dropped to 24.5%, mainly due to the increase in total projected area and the additional energy required to operate the water pump. Overall, the thermal efficiency values obtained in this study are consistent with those reported in similar works, while the improvement in water productivity (especially in enhanced configurations) is notably higher, demonstrating the effectiveness of the integrated modifications. Recent studies have investigated the use of phase change materials (PCMs), nanomaterials, innovative geometries, and supplementary enhancements to boost solar still performance, as detailed in Table 1. This table compiles selected recent research, outlining the still type, PCM integration approach, and key results related to thermal efficiency, freshwater yield, and cost-effectiveness. These studies emphasise the increasing adoption of hybrid and multifunctional designs to overcome the constraints of traditional solar desalination systems.

Table 3. Summary of solar still studies using PCM, with still type, integration method, and key performance outcomes.

Study	Still Type	PCM & Integration Method	Key Findings
Arunkumar et al. (2013) [120]	SBSS	Copper balls filled with PCM	Yield increased by 87.4% over conventional.
Shalaby et al. (2016) [121]	SBSS	Paraffin wax in a galvanised steel tank under a V-corrugated plate	Overnight yield improved by 72.7%; total daily output increased by 11.7%.
Elfasakhany (2016) [122]	SBSS	Cu/paraffin nanocomposite	Distillate yield increased by 125%.
Kabeel & Abdelgaied (2016) [123]	SBSS	Paraffin wax + copper absorber	67% increase in distillate yield over a conventional still.
Sharshir et al. (2017) [124]	SBSS	PCM + graphite flakes; film cooling	Productivity improved by 50.8% (up to 73.8% with cooling).
Thakur et al. (2017) [125]	SBSS	Paraffin wax below the absorber plate	Thermal efficiency reached 41.46%; daily yield ~5.1 L/day.
Saeed et al. (2019) [126]	SBSS	3% Al_2O_3 nanoparticles in paraffin	Productivity increased by 20%.
Yousef & Hassan (2019) [127]	SBSS	Paraffin wax + steel wool fiber (SWF)	Yield 13% higher than conventional.
Cheng et al. (2019) [128]	PSS	Expanded graphite + PCM	Yield increased from 21.5% to 57.5%; conductivity improved.
Kabeel et al. (2020) [129]	PSS	Hollow cylindrical pin fins in PCM	Yield doubled; 101.5% improvement.
Mohammed et al. (2021) [130]	SBSS	Paraffin wax (2, 4, 6 kg)	An optimal 4 kg PCM gave 30% improvement in productivity.
Jahapanah et al. (2021) [131]	SBSS	Aluminium-coated PCM packs (salt hydrate)	30.3% increase in yield; 36.4% rise in efficiency.
Madhu et al. (2021) [132]	HSS	Aluminium cans with PCM (square & triangular array)	Productivity improved by 94% (square) and 67% (triangular).
Dhindsa (2021) [133]	SBSS	Paraffin wax with a floating wick	Productivity improved by 32%.
Behura & Gupta (2021) [134]	SBSS	Paraffin wax + CuO nanoparticles	Nano-PCM improved productivity by 35%.
Kumar et al. (2021) [134]	SBSS	PCM, PCM+0.5% silica (n-PCM)	Water yield improved by 51% (PCM) and 67% (n-PCM).
Kumar et al. (2022) [135]	SBSS	Nano-zinc disbanded PCM	Distillate yield is 50% higher than conventional.
Abdullah et al. (2022) [136]	SBSS	Paraffin + 2.5% wt nano black paint	Productivity enhanced by 112%.
Sampathkumar & Natarajan (2022) [137]	SBSS	MicroPCM with eucheuma powder	Distillate yield increased by 30%.
Ahmed et al. (2023) [138]	PSS	Paraffin wax encapsulated in cylindrical fins (40 mm height)	Finned PCM still enhanced efficiency by 44.4% compared to conventional; cost per litre reduced to $0.043.
Afolabi et al. (2023) [7]	DSSS	Microencapsulated PCM in epoxy resin composite	Yield improved by 105%, operation extended by 3 hours, and payback period shortened to 0.8 years.
Murali et al. (2024) [139]	SBSS	Paraffin wax and Al_2O_3 nano-PCM in copper tubes	Nano-PCM boosted productivity by 60.37% and efficiency by 68.29% over baseline.

Essa et al. (2024) [140]	HSS	Silver nano-PCM beneath absorber with baffles and reflectors	Yield enhanced by 245%; efficiency achieved 65%.
Elamy et al. (2024) [141]	COSS + VWSS	Paraffin wax with silver nanoparticles, condenser, and reflectors	Yield increased by 246%; cost per litre reduced to \$0.0126.
Hemmatian et al. (2024) [142]	SBSS	Paraffin wax in a pulsating heat pipe and thermosyphon with evacuated tubes	Productivity improved by 40.7%; cost per litre lowered to \$0.0458/L.
Alqsair et al. (2024) [143]	HSS	Silver nano-PCM with fan, reflectors, and jute wick	Productivity rose by 172%; daily yield reached 11,150 mL/m².
Anika et al. (2024) [144]	PSS	Hybrid nano-PCM (Al_2O_3 + ZnO) with fins, sponge, and black sand	Yield increased by 92%; cost per litre reduced by 81.89%; exergy efficiency improved by 74.75%.
Patel et al. (2025) [145]	PSS	Paraffin in trays, cans, and finned copper tubes	PCM in cans yielded optimal results: 57.7% increase in yield, 36.5% energy efficiency, and \$0.0152/L cost.
Sathish et al. (2025) [146]	SBSS	Paraffin wax with 0.3–0.9 wt% graphene oxide in a tube absorber	0.9% GO–PCM increased water yield by 33.9% and thermal efficiency by 68.7%.

Table 3 provides a comprehensive overview of experimental studies on solar stills integrated with encapsulated phase change materials (PCMs) to enhance desalination performance, predominantly single-basin solar stills (SBSS). The table reveals a strong emphasis on paraffin wax as the primary PCM due to its high latent heat and cost-effectiveness, often augmented with innovative additives like Cu/paraffin nanocomposites, Al_2O_3 nanoparticles, graphite flakes, or black gravel to improve thermal conductivity and storage capacity. Integration methods vary, including copper balls, galvanised steel tanks, aluminium cans in square or triangular arrays, and hollow cylindrical pin fins, reflecting a focus on optimising heat transfer and retention. Performance outcomes are striking, with freshwater yield increases ranging from 11.7 [121] to 125% [122] over conventional stills, driven by enhanced evaporation rates and extended operational periods, particularly at night, where PCMs release stored heat (e.g., 72.7% overnight yield improvement in [121]. Hybrid systems combining PCMs with cooling films, solar concentrators, or nano-enhanced materials achieve even greater gains, such as Sharshir et al.'s [122] 73.8% productivity boost with film cooling and Abdullah et al.'s 112% increase with nano black paint. Energy and exergy efficiencies also improve significantly. The table underscores a trend toward combining PCMs with structural and material innovations to maximise distillate output, with studies like Kabeel et al. (2020) [129] doubling yields through optimised designs. Recent studies (Ahmed et al., 2023 [138]; Afolabi et al., 2023 [7]; Murali et al., 2024 [139]; Essa et al., 2024 [140]; Patel et al., 2025 [145]; have achieved remarkable yield improvements (up to 246%) and efficiencies (e.g., 68.7% thermal efficiency in Sathish et al., 2025 [146]) through innovative PCM integrations. These recent studies emphasise nano-enhanced PCMs (e.g., silver, Al_2O_3, ZnO, graphene oxide) and hybrid systems with reflectors, baffles, condensers, or wicks, significantly boosting productivity (e.g., 11,150 mL/m² daily yield in Alqsair et al., 2024 [143]) and reducing costs (e.g., \$0.0126/L in Elamy et al., 2024 [141]). Additionally, they extend operational periods (e.g., 3 hours in Afolabi et al., 2023 [7]) and improve exergy efficiency (e.g., 74.75% in Anika et al., 2024 [144]), reflecting a shift toward cost-effective, high-performance designs. However, the wide range of yield gains (33.9% to 246%) and cost reductions (\$0.0126/L to \$0.0458/L) underscores the need for standardized testing and scalable solutions to optimize PCM integration for practical solar desalination applications. However, the variability in yield improvements (11.7% to 125%) suggests that performance is highly dependent on PCM type, integration method, and system design, pointing to future research directions in standardizing optimal configurations and exploring cost-effective, scalable solutions for broader adoption in solar water systems.

4.3. Solar pond technique

Solar ponds (SPs) are large-scale systems that capture solar radiation through a salinity gradient to store heat in the lower convective zone (LCZ), functioning as efficient reservoirs for heat storage and low-grade energy applications. However, challenges such as heat loss and unstable temperature gradients can hinder their performance. Incorporating encapsulated phase change materials (PCMs) into solar ponds has proven to be an effective approach to improve thermal stability, minimise diurnal temperature swings, and enhance energy storage efficiency. By integrating PCMs into cylindrical vessels or heat exchangers within the pond's layers, studies have shown more consistent thermal profiles, better salinity stability, and, in some instances, higher thermal efficiency.

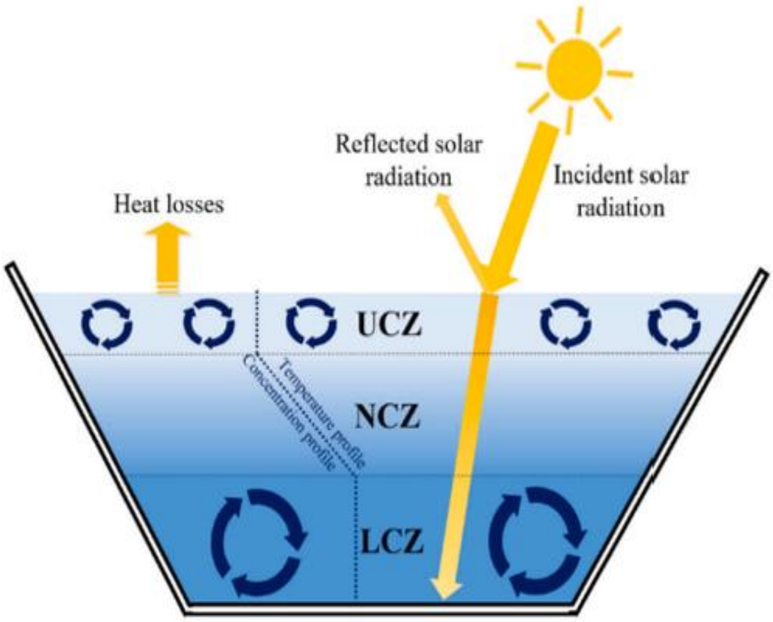

Fig. 9. Configuration of a salt-gradient solar pond system [147].

Table 4 compiles research from 2015 to 2025 on the integration of Phase Change Materials (PCMs) in Solar Ponds (SPs) and Salinity Gradient Solar Ponds (SGSPs) across various locations, including Iran, Italy, Turkey, Morocco, China, Saudi Arabia, and India. The studies, employing experimental, numerical, or combined approaches, consistently demonstrate that PCMs enhance thermal stability, reduce temperature fluctuations, and improve heat retention in SPs and SGSPs. Key findings include efficiency gains (e.g., 6.1% in series layouts, 84.6% thermal efficiency with heat exchangers), improved energy storage (up to 9.6% with optimal PCM thickness), and enhanced performance with nanoparticle additives (e.g., 17.31% conductivity increase with Al_2O_3, 28.3% LCZ temperature rise with soot). Innovations like aluminium-encapsulated PCMs and PCM-TES integration further boost durability and load management. However, challenges such as low solar energy storage (6% in some cases) highlight the need for optimised insulation and geometry to minimise heat loss. These findings underscore PCMs' potential to advance solar pond performance, particularly in diverse climatic conditions.

Table 4. Summary of Studies on Phase Change Materials (PCMs) in Solar Ponds (SPs) and Salinity Gradient Solar Ponds (SGSPs)

Reference	Configuration	Location	Study Type	Key Findings
Assari et al. (2015) [148]	SGSP with cylindrical PCM capsules	Dezful, Iran	Experimental	Decreased temperature fluctuations and improved thermal/salinity consistency. PCM ensured stable thermal regulation.

Amirifard et al. (2018) [149]	SP with PCM in series/parallel arrangements	Dezful, Iran	Numerical	Boosted discharge efficiency by 6.1% (series) and 5.4% (parallel).
Beik et al. (2019) [150]	PCM capsules in LCZ	Dezful, Iran	Numerical & Experimental	Stored only 6% of solar energy; proper insulation and SP design minimised heat loss.
Ines et al. (2019) [151]	SGSP under solar simulator with/without PCM	Ancona, Italy	Experimental	PCM-integrated SP exhibited reduced temperature variation and lower heat loss.
Assari et al. (2020) [152]	SPs with varied NaCl–Na_2SO_4 PCM blends	Dezful, Iran	Experimental	Na_2SO_4 enhanced stability; 0.75% concentration optimised heat extraction.
Rghif et al. (2021) [153]	SGSP with PCM and Dufour effect	Tangier, Morocco	Numerical	PCM reduced the Dufour effect impact and limited thermal efficiency losses.
Farsijani et al. (2021) [154]	SP with internal/external heat exchanger and PCM	Tehran, Iran	Experimental	PCM raised thermal/exergy efficiencies to 84.6% and 15.9%, respectively.
Wang et al. (2021) [155]	SP with paraffin PCM (P50, P60) in LCZ	Henan, China	Experimental & Numerical	PCM minimised temperature swings; higher latent heat reduced flow.
Assari et al. (2022) [156]	SP with/without PCM	Dezful, Iran	Experimental & Analytical	PCM-enhanced SP showed better thermal endurance, reduced evaporation, and superior heat retention.
Boskurt (2022) [157]	SP with glass wool and paraffin-based PCMs	Adana, Turkey	Experimental	Improved thermal insulation and stability; paraffin 46 proved most effective.
Colarossi & Principi (2022) [158]	SGSP with 10% LCZ volume of RT35 HC-PCM	Ancona, Italy	Numerical	PCM enhanced energy storage and maintained pond temperature stability.
Colarossi et al. (2022) [159]	SP with metal PCM tubes at the LCZ base	Ancona, Italy	Experimental	Improved long-term heat storage and temperature consistency.
Rayanoshh & Kartikeyan (2022) [160]	PCM in a cylindrical capsule in LCZ	India	Numerical	PCM increased LCZ stability by 8–9%, varying with layer thickness.
Sogukpinar et al. (2023) [161]	SGSP with PCM of varying thickness	Adana, Turkey	Experimental	PCM enhanced heat storage; optimal thickness achieved 9.6% efficiency gain.
Choubani et al. (2024) [162]	SGSP with aluminium-encapsulated PCM	Riyadh, Saudi Arabia	Experimental	Improved durability and heat retention with aluminium PCM casing.
Colarossi & Rghif (2024) [163]	SGSP with PCM and TES	Ancona, Italy	Numerical & Experimental	PCM-TES integration enhanced energy retention and load management.
Pawar et al. (2024) [164]	SGSP with varying PCM ratios and melting points	India	Experimental	Enhanced storage capacity, temperature uniformity, and efficiency.
Poyyamozhi et al. (2024) [165]	SP with paraffin and 1–3 wt% soot nanoparticles	Tamil Nadu, India	Experimental	2 wt% soot in paraffin raised the LCZ temperature by 28.3% and enhanced thermal efficiency in hot climates.
Singh et al. (2025) [166]	SP with OM-37 PCM and Al_2O_3 nanoparticles	Dadri, India	Experimental	2% Al_2O_3 increased PCM conductivity by 17.31%; SP thermal efficiency reached 15.1%; heat retention improved by ~30 W over baseline PCM.
Poorani et al. (2025) [167]	SP with paraffin wax and Fe_3O_4 nanoparticles	India	Experimental	2 wt% Fe_3O_4 boosted thermal storage by 23.7%; paraffin-Fe_3O_4 composites improved conductivity and stabilized energy output.

Assari et al. (2015) [148] experimentally studied two small-scale salinity-gradient solar ponds (SGSPs) with a horizontal cylindrical PCM cavity in the lower convective zone (LCZ), as shown in Figure XY, using an internal heat exchanger. The addition of PCM reduced day-night temperature fluctuations and improved thermal and salinity stability, though thermal efficiency decreased, which could be mitigated by lengthening the heat exchanger pipe. PCM integration was found beneficial for applications requiring uniform temperatures.

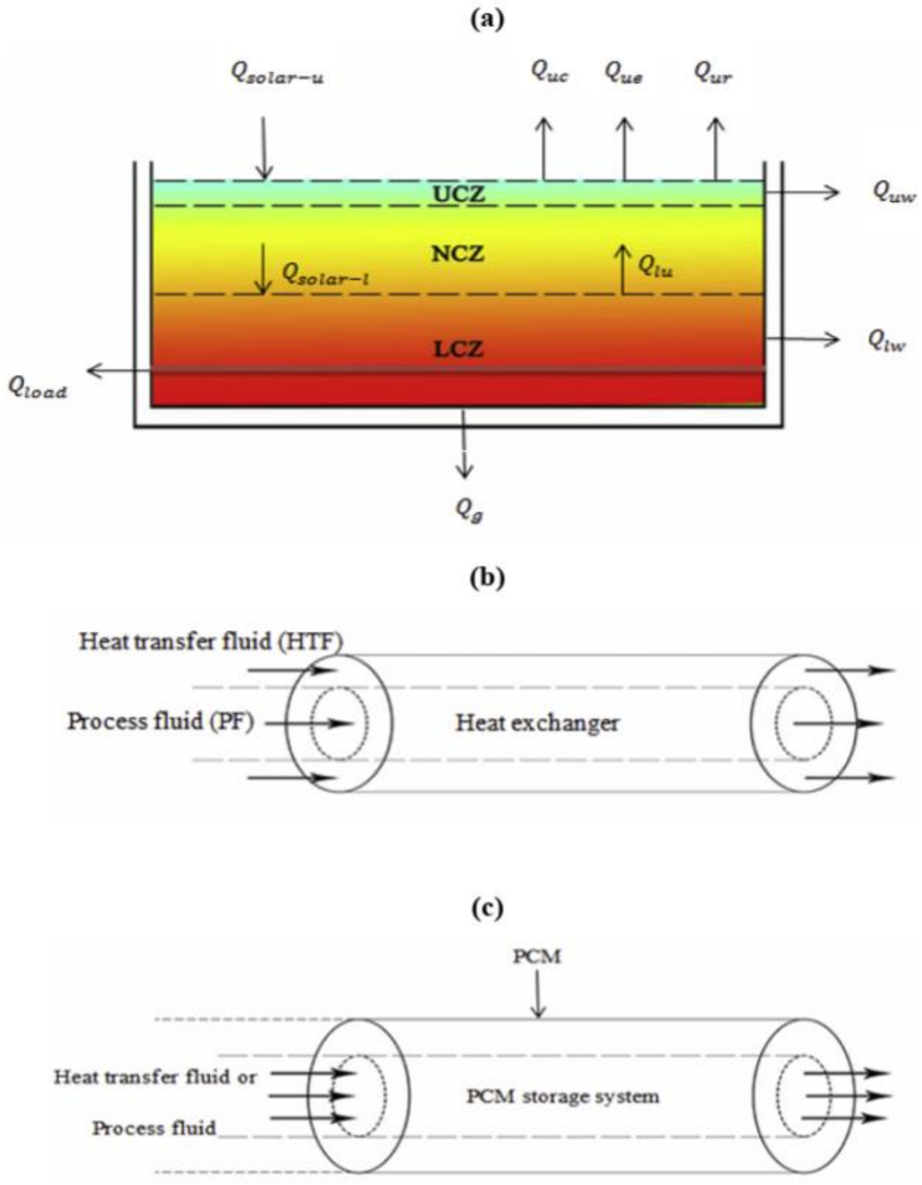

Fig. 14. Illustration of the system components: a) solar pond with built-in heat exchanger, b) external heat exchanger, c) phase change material (PCM) storage unit [149].

Amirifard et al. (2018) [149] numerically analysed SP-PCM systems in three configurations (one series and two parallel layouts, Figure 14), reporting average efficiency increases of 6.1% and 5.4% for series and parallel setups, respectively, compared to SP without PCM. Beik et al. (2019) [150] conducted experiments and developed a validated one-dimensional unsteady thermal model for an SP-PCM system, accounting for conduction, convection, and radiation heat transfer to predict UCZ temperature. PCM cylindrical vessels in the LCZ stored only 6% of solar insolation, with significant losses via walls, evaporation, reflection, and convection; losses were minimised with insulation and were negligible for depth-to-diameter ratios below 0.015, while PCM ensured stable heat extraction. Ines et al. (2019) [151] compared two mini SGSP systems (with and without hydrate salt PCM, Figure 6) under a solar simulator with and without a UV filter, finding the non-PCM system reached higher average temperatures, but the SP-PCM system had lower temperature differences with ambient and reduced heat loss, enabling simultaneous energy collection and storage for domestic hot water. Rghif et al. (2021) [153] numerically studied the Dufour effect and PCM layer at the SGSP bottom, noting that PCM increased surface heat losses and reduced LCZ/NCZ temperatures and efficiency, but mitigated the Dufour effect's impact, which lowered storage efficiency by 4.67% (SP-PCM) and 5.56% (SP) as the Dufour coefficient rose from 0 to 0.8. Wang et al. (2021) [155] studied SP with Paraffin 60 and Paraffin 50 PCMs in the LCZ, finding that PCM reduced temperature variations during phase changes, suppressed flow in the heat storage zone, with larger latent heat PCMs showing stronger suppression, though effects diminished post-phase change. Bozkurt (2022) [60] numerically assessed the application of three different PCMs in a solar pond (SP) for insulation to extend thermal energy storage. The simulations indicated that SP-PCM systems achieved heat storage ratios of 47.81% for paraffin 44, 34.85% for capric acid, and 32.22% for paraffin C18 in December (Fig. 12). In contrast, SPs with glass wool insulation exhibited storage ratios between 7.92% and 20.95%.

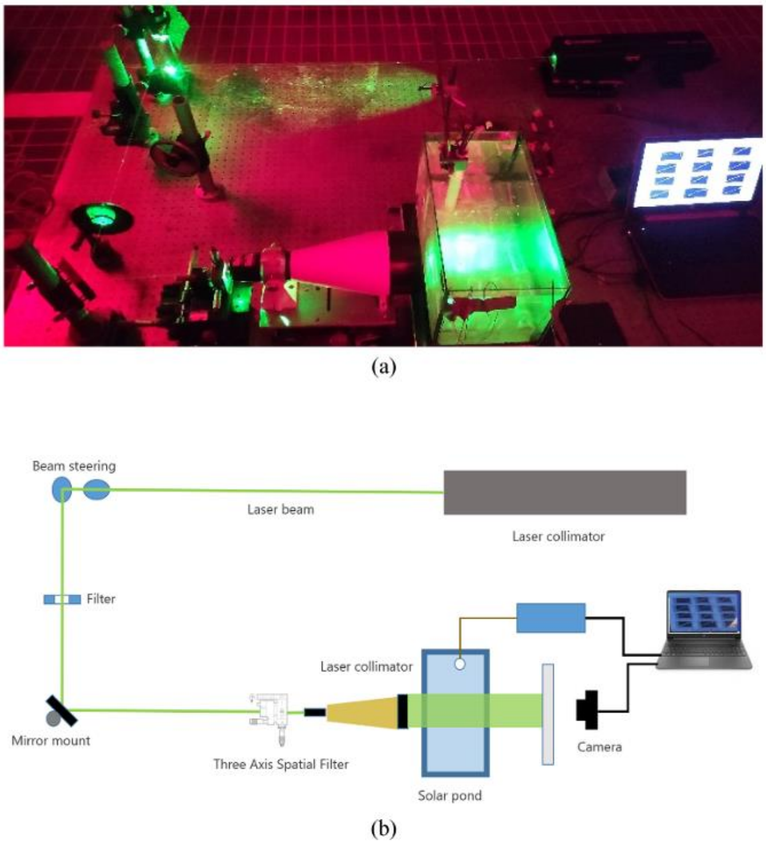

Figure 21 (a): The real optical system, and (b): the schematic system [158]

An experimental study was conducted by Colarossi and Principi (2022) [158] (Figure 21) to enhance the thermal performance and stability of solar ponds by incorporating paraffin wax, encapsulated in aluminium cylinders, into the lower convective zone (LCZ) of a small-scale salinity gradient solar pond. This approach aimed to reduce heat loss to the ground and improve thermal energy storage through the latent heat properties of the phase change material (PCM). Temperature data revealed that the LCZ in the PCM-enhanced pond was approximately 3 °C cooler than the reference case after six hours of solar heating, indicating lower thermal losses and better energy storage. Additionally, optical visualisation using laser shadowgraph techniques showed significantly reduced convection currents in the PCM-integrated system, leading to improved stratification stability. The PCM-enhanced system maintained superior thermal layering, reduced interface disturbances, and exhibited greater durability, making it a promising approach for enhancing energy retention and operational stability in solar pond applications.

Subsequently, Colarossi et al. (2022) [159] experimentally investigated the influence of two PCMs (RT44 HC and RT35 HC) on SP thermal properties (Fig. 13). PCM integration enhanced thermal stability and minimised heat losses. Without PCM, the SP bottom reached a peak temperature of 52.4 °C, compared to 49.3 °C with PCM. Higher PCM melting temperatures mitigated temperature peaks, while lower melting temperatures ensured better nighttime temperature stability.

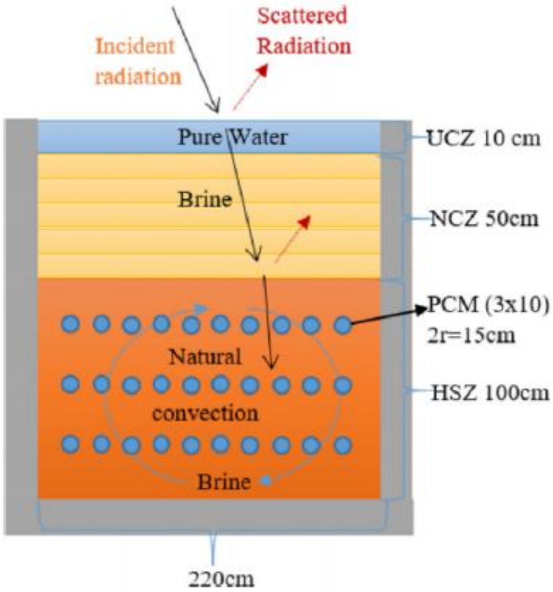

Fig. 17 Solar pond with PCM integration [161].

Sogukpinar et al. (2023) [161] conducted experimental and numerical studies on the long-term performance of an SP-PCM system (Figure 17), testing fatty acids and paraffin derivatives. The results indicated maximum SP efficiencies of 24.58% for camphene in November and 22.57% for paraffin C20-C33 in December, with camphene proving optimal for thermal storage enhancement. The study also found that increasing the PCM mass ratio at a fixed melting temperature or raising the melting temperature at a fixed mass ratio reduced the PCM liquid fraction. Elevating both parameters lowered PCM temperature and improved SP stability. Pawar et al. (2024) [164] designed an SP with PCM, thermal energy storage (TES), a transparent cover, cork sheet side insulation, and two coating types (synthetic enamel paint and epoxy). Experiments assessed the effects of thermal insulation, bottom reflectivity, and water turbidity. PCM integration led to a temperature reduction, while TES increased average temperatures and improved thermal energy storage and release. Singh et al. (2025) [166] reported that adding 2% Al_2O_3 nanoparticles to OM-37 PCM in an SP increased thermal conductivity by 17.31%, achieving a thermal efficiency of 15.1% and improving heat retention by approximately 30 W compared to baseline PCM. Similarly,

A	B

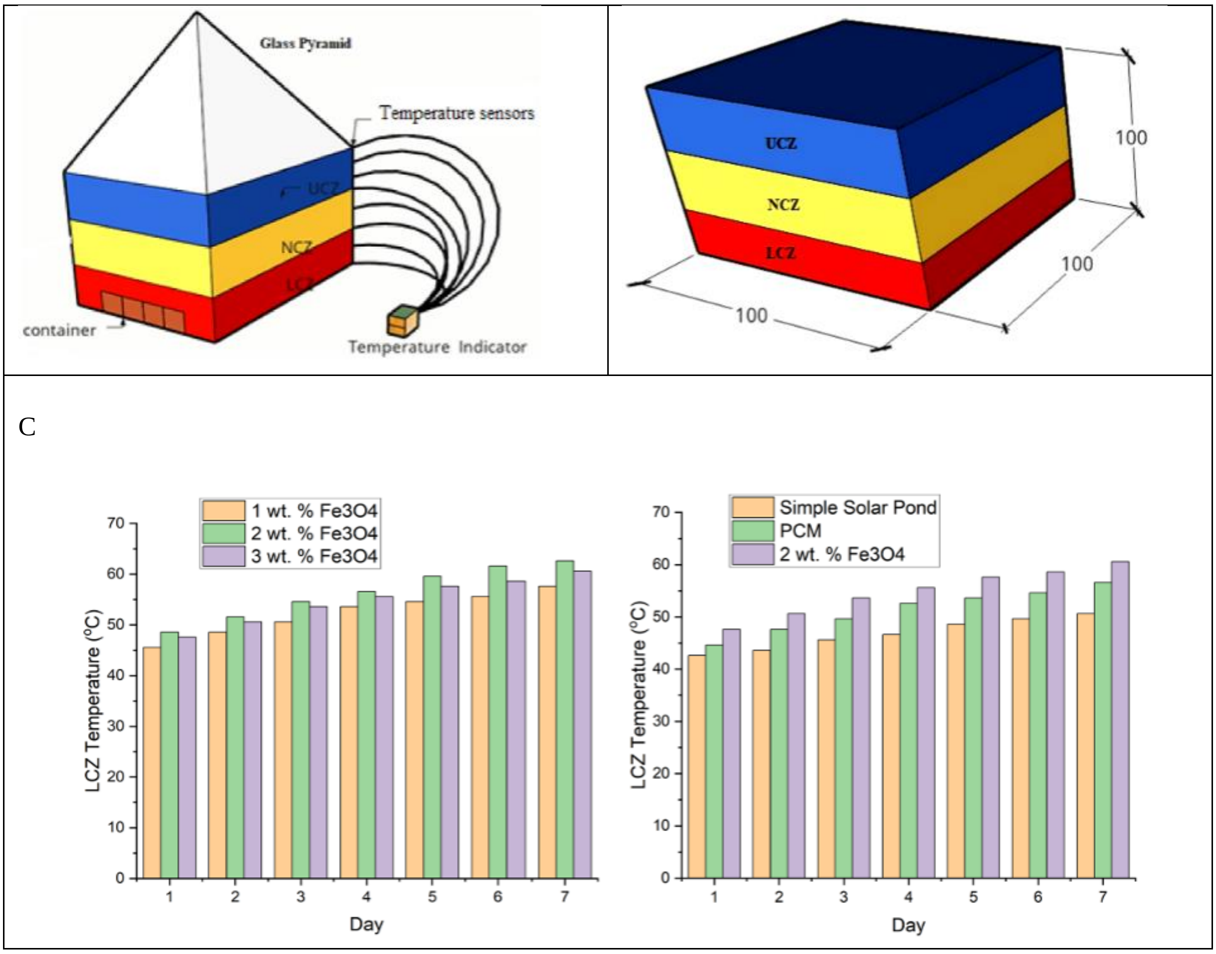

Figure 15: A: experimental setup, B: Solar pond dimensions and C: Average temperature variations of Lower Convective Zone (LCZ) during the initial week for different solar pond configurations with varying Fe_3O_4 concentrations and PCM [167].

Poorani et al. (2025) [167] found that incorporating 2 wt% Fe_3O_4 nanoparticles into paraffin wax enhanced thermal storage by 23.7%, with paraffin-Fe_3O_4 composites improving conductivity and stabilising energy output (Figure 15). Innovations like aluminium-encapsulated PCMs and PCM-TES integration further boost durability and load management. However, challenges such as low solar energy storage (6% in some cases) highlight the need for optimised insulation and geometry to minimise heat loss. These findings underscore PCMs' potential to advance solar pond performance, particularly in diverse climatic conditions, with nanoparticle-enhanced PCMs showing significant promise for further improving efficiency and stability.

4.4. Solar Water Tank

Solar water tanks are critical components of solar thermal systems, serving as thermal energy storage units to provide hot water during periods without sunlight [168-171]. Incorporating encapsulated phase change materials (ePCMs) into these tanks significantly enhances thermal storage capacity, stabilises discharge, and reduces heat losses. Compared to bulk PCM, ePCMs offer faster heat exchange, reduced supercooling, and improved integration within tank designs. This subsection reviews recent advancements in using ePCMs in solar water tanks to optimise thermal regulation and energy delivery for residential and industrial applications.

One/two Figures

Table 5. Summary of Studies on Solar Water Tanks Integrated with Encapsulated Phase Change Materials (ePCMs).

Ref/Author (Year)	System Configuration	PCM Type	Encapsulation Method	PCM Placement	Key Objectives	Key Findings
Cabeza et al. (2006) [172]	Pilot tank with PCM module	Sodium acetate + graphite	Cylindrical modules	Tank top	Test PCM integration	Enhanced stratification and energy storage
Solé et al. (2008) [173]	Water tank with PCM spiral coil	Sodium acetate + graphite	Spiral coil	Tank top	Assess energy/exerg y performance	Improved thermal retention and exergy efficiency
Castell et al. (2009) [174]	Traditional vs. PCM-enhanced tank	Unspecifi ed PCM	Likely macroencapsulation	Tank top	Compare stratification effects	Extended hot water delivery with PCM
Padovan & Manzan (2014) [175]	SDHW system with PCM tank	Unspecifi ed PCM	Optimised via genetic algorithm	Inside tank	Optimise tank geometry and insulation	PCM is less effective than optimised geometry/insulation
Huang et al. (2019) [176]	Stratified tank with PCM at varying heights	Sodium acetate trihydrate	Macroencapsulation	Top, middle, bottom	Study stratification vs. flow rate	Optimal stratification with bottom-placed PCM at >0.42 m³/h
Huang et al. (2019) [177]	PCM unit in series with water tank (TRNSYS)	Sodium acetate trihydrate	Shell-and-tube	In series with a tank	Boost solar efficiency	The series configuration increased solar fraction by ~30%
Dhaou et al. (2022) [178]	SWT with nano-enhanced PCM and stirrer	Nano-enhanced PCM	Cylindrical capsules	Jacketed/spir al heat exchanger	Analyse stirring effects	Stirrer reduced charge/discharge times by 12.5% and 23.5%
Eldokaishi et al. (2022) [179]	ANN model for PCM solar tank	Unspecifi ed PCM	Numerical model	System model	Develop optimised design maps	ANN achieved R^2 = 0.9999, 10^5 times faster modeling
Kong et al. (2022) [180]	Hybrid PCM and water tank	Unspecifi ed PCM	Numerical CFD	Separate regions	Build an accurate numerical model	Energy balance error <5%, effective stratification with supercooling
Cao et al. (2022) [181]	Water/NEPCM convection to PCM tank	Nano-enhanced PCM	Nano core-shell	External flow path	Simulate CFD heat exchange	3% NEPCM increased heat flux by 22.2%
Zakri et al. (2022) [182]	Numerical test of three PCM tank layouts	Unspecifi ed PCM	Tubes + external jacket	Around tank	Evaluate geometry and PCM properties	PCM properties critical; 70% efficiency with encapsulated jacket

Yari et al. (2023) [183]	Spherical double-wall tank with PCM	Unspecified PCM	Outer chamber	Surrounding tank	Eliminate insulation, improve solar gain	Achieved 80.3°C max temperature, 74% efficiency, optimal stratification at 1.25 l/min
Huang et al. (2025) [184]	S-shaped PCM water tank	Unspecified PCM	Integrated into the channel	S-channel zone	Enhance the heat transfer rate	S-tank achieved 18% faster storage than a traditional PCM tank
Jabbar et al. (2025) [185]	TES tanks with PCM, gravel, and water	PCM, water, gravel	Likely macroencapsulation	Inside tank	Compare heat storage materials	PCM stored 135% more energy than water, 770% more than gravel

Table 5 provides an in-depth overview of research on solar water tanks integrated with encapsulated phase change materials (ePCMs), highlighting their role in enhancing thermal energy storage for solar thermal systems. The studies span experimental, pilot, and numerical scales, with a focus on improving energy storage, thermal stratification, and system efficiency across various climatic conditions, ranging from temperate to arid environments (20–45°C ambient temperatures). Sodium acetate trihydrate (melting temp ~58°C) and nano-enhanced PCMs, such as paraffin with additives like Cu nanoparticles, are frequently used due to their high latent heat and improved thermal conductivity. Encapsulation methods, including cylindrical modules, spiral coils, shell-and-tube, and nano core-shell designs, optimise heat exchange and integration within tank geometries, with placements varying from tank tops to external jackets. Key performance outcomes demonstrate significant advancements: PCMs increase energy storage by up to 135% compared to water and 770% compared to gravel, extend hot water delivery by 25%, and achieve efficiencies of 70–82%. Innovations like nano-enhanced PCMs (e.g., Cao et al., 2022 [181] and mechanical stirrers Dhaou et al., 2022 [178] reduce charge/discharge times by up to 23.5% and enhance heat flux by 22.2%. Novel designs, such as the S-shaped tank Huang et al., 2025 [184], achieve 18% faster storage, while series configurations Huang et al., 2019 [177] boost solar fraction by ~30%. Numerical modelling, including CFD and ANN approaches, provides high accuracy (e.g., $R^2 = 0.9999$ in Eldokaishi et al., 2022 [179] and faster design optimisation, though reliance on unspecified PCMs in several studies e.g., Castell et al., 2009 [174] and Zakri et al., 2023 [183] limits comparability. Despite these advancements, challenges persist. The variability in PCM types, encapsulation methods, and placement strategies highlights a lack of standardisation, which hinders scalability and cost-effectiveness. The absence of reported melting temperatures in multiple studies complicates the assessment of PCM suitability for specific climates or applications. Additionally, most studies focus on short-term performance under controlled or simulated conditions, with limited exploration of long-term durability, maintenance costs, or real-world performance under fluctuating solar inputs. Future research should prioritise standardised PCM characterization, parametric studies on encapsulation designs, and field testing across diverse operational conditions to bridge these gaps and enhance practical adoption in residential and industrial settings.

5. Conclusion

This review comprehensively examines the pivotal role of micro- and nano-encapsulated phase change materials (M/N-ePCMs) in advancing the performance of solar water systems. These materials are increasingly incorporated into solar thermal applications, including water heaters, solar stills, solar ponds, and storage tanks, due to their exceptional ability to efficiently absorb, store, and release thermal energy. The encapsulation process enhances thermal conductivity, prevents leakage, and improves material durability, ensuring robust performance under real-world cyclic conditions. Key findings from the literature include the following:

- ✓ First, ePCMs significantly improve thermal retention, sustaining water temperatures over extended periods and stabilising output during non-sunlit hours.
- ✓ Second, advanced micro- and nanoscale encapsulation techniques enhance PCM stability and heat transfer, making them ideal for long-term solar water applications.
- ✓ Third, the strategic placement of PCMs within tanks—whether at the top, bottom, or in cascaded configurations—greatly impacts thermal stratification and efficiency.
- ✓ Fourth, innovative tank designs, such as spiral coils or S-shaped channels, accelerate heat transfer and reduce system response times. Advanced modelling tools, including Artificial Neural Networks (ANNs) and Computational Fluid Dynamics (CFD), have proven effective in predicting, optimising, and validating the thermal performance of ePCM-integrated systems with reduced computational demands. Comparative analyses demonstrate that ePCM-enhanced tanks outperform gravel- or water-based tanks in energy storage capacity and heat loss reduction. In solar stills, ePCMs maintain elevated basin temperatures after sunset, significantly increasing freshwater yields beyond daylight hours. Novel designs, such as spherical or jacketed PCM tanks and nano-enhanced PCM (NEPCM) systems, show superior solar absorption and system efficiency.

Despite these advancements, critical areas for future research include:

- In-depth studies on the long-term thermal stability and cyclic reliability of ePCMs in aqueous environments.
- Development of cost-effective, scalable encapsulation methods for large-scale solar water systems.
- Exploration of hybrid encapsulation techniques combining physical and chemical approaches for enhanced performance.
- Assessment of the environmental compatibility of encapsulation materials with drinking and domestic water standards.
- Integration of ePCM tanks with smart control systems and sensors for real-time thermal management and performance monitoring.
- Application of AI-driven optimisation and predictive maintenance to improve system responsiveness and longevity.
- Comparative analysis across solar water applications (heating, distillation, storage) to determine optimal encapsulation materials and configurations.

By consolidating these insights, this review lays the foundation for developing next-generation solar water technologies that are efficient, scalable, and tailored for water-scarce and off-grid regions, addressing the pressing global demand for clean energy and freshwater.

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