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Micro-/nano-encapsulated phase change materials: Revolutionising heat transfer fluids for solar energy applications

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ABSTRACT

Micro- and nano-encapsulated composite phase change material-based heat transfer fluids represent a promising advancement for solar energy systems by significantly enhancing heat transfer and thermal energy storage capabilities. This review addresses the critical limitations of conventional heat transfer fluids, such as low thermal conductivity and limited energy storage capacity, which hinder solar thermal system performance and efficiency. The integration of advanced encapsulated phase change materials is hypothesized to overcome these challenges by simultaneously augmenting thermal storage capacity and heat conduction, thus optimizing the overall solar system performance. This paper systematically reviews recent progress in the selection of phase change materials tailored for solar applications, innovative encapsulation techniques, and the development of micro- and nano-encapsulated composite fluids with improved thermophysical properties. Applications in various solar thermal systems are examined to highlight their practical potential. Key findings from experimental and theoretical studies demonstrate that these advanced composite materials and fluids can improve thermal conductivity by up to 471 % and enhance energy storage efficiency by 92 % compared to traditional materials and heat transfer fluids. Despite these promising results, challenges remain, including scalability of manufacturing processes, long-term thermal and chemical stability, and environmental sustainability of materials. The review emphasizes the need for further research focused on scalable production methods, durability testing, and eco-friendly material development. Overcoming these obstacles is essential to enable broader commercial adoption. Ultimately, these innovations hold the potential to significantly boost the cost-effectiveness, reliability, and sustainability of solar thermal technologies, contributing to a faster global transition toward renewable energy sources.

1. Introduction

The swift increase in the global population, economies, and technology has driven an unprecedented surge in energy demand. Industrialisation, urbanisation, and technological progress have increased energy consumption across sectors like manufacturing, transportation, and residential applications [1]. Fossil fuels—natural gas, coal, and oil—remain dominant due to their high energy density, established infrastructure, and economic viability [2]. Their extensive, however, use has made them a primary contributor to climate change, releasing large quantities of carbon dioxide (CO_2) and other greenhouse gases, such as nitrous oxide and methane, into the atmosphere [3]. These emissions have intensified the greenhouse effect, causing higher global temperatures, escalating sea levels, thawing ice caps, and intensified extreme weather [4]. The severe environmental impacts of fossil fuel reliance underscore the urgent need for sustainable energy solutions that balance environmental preservation with long-term energy security and economic stability [5].

In response, the global transition to net-zero CO_2 systems has become a critical objective, requiring a fundamental shift in energy production and consumption patterns [6]. Achieving this goal, however, demands technological innovation, supportive policies, and international collaboration to accelerate renewable energy adoption [7]. Governments, industries, and researchers have been working to reduce fossil fuel dependence by integrating cleaner energy alternatives, deploying carbon capture and storage technologies, and improving energy efficiency [8]. Decarbonising energy-intensive sectors—such as power generation, transportation, and industrial manufacturing—is essential for achieving a net-zero future [9]. Market incentives, regulatory policies, and

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Nomenclature

PV	Photovoltaic
TES	Thermal energy storage
PCM	Phase change material
HTF	Heat transfer fluid
PCM-HTF	Micro-/nano-encapsulated composite PCM-based HTF
CSP	Concentrated solar power
PMMA	Polymethyl methacrylate
PLA	Polylactic acid
UF	Urea-formaldehyde
PU	Polyurea
P(MMA-co-MA)	Poly(methyl methacrylate-co-methyl acrylate)
MUF	Melamine–urea–formaldehyde
PEG	Polyethylene glycol
CCHH	Calcium chloride hexahydrate
$NaNO_3$	Sodium nitrate
OA	Octanoic acid
CA	Decanoic acid
SSD	Sodium sulphatedecahydrate
PV/T	Photovoltaic/thermal
mPCS	Microencapsulated phase change slurry
PLA	Polylactic acid
MF	Melamine-formaldehyde
PS	Polystyrene
SiO_2	Silica
$CaCO_3$	Calcium carbonate
TiO_2	Titanium dioxide
ZnO	Zinc oxide
ZrO_2	Germanium dioxide
AlOOH	Aluminum hydroxide
$PbWO_4$	Lead tungstate
Fe_3O_4	Magnetite
AlN	Aluminum nitride
MnO_2	Manganese dioxide
$CH_3COONa\cdot 3H_2O$	Sodium acetate trihydrate
KNO_3	Potassium nitrate
SAT	Sodium acetate trihydrate
TD	Tetradecane
DA	Dodecanol
SPDD	Sodium phosphatedibasic dodecahydrate
PCS	Phase change slurry
MPCM	Microencapsulated PCM
LCA	Life-cycle assessment

investments in renewable energy infrastructure are also critical drivers of this transition [10].

The Intergovernmental Panel on Climate Change highlights that diversifying energy production is key to reducing global net emissions by 2030. Solar and wind energy stand out for their potential to deliver low-cost energy whilst significantly lessening greenhouse gas emissions. Wind and solar energy have the highest annual net emission reduction potential, estimated at approximately 4.5 and 4 gigatons of CO_2-equivalents, respectively [11]. They are also among the most cost-effective options, with mitigation costs below USD 20 per tonne of CO_2-equivalent [1]. Beyond emission reductions, these renewable sources enhance energy diversification, improve grid stability, and support demand-side management strategies, such as energy efficiency improvements and storage, ultimately strengthening global energy security [12].

Solar energy, in particular, has significant potential to reduce net emissions and is one of the most promising renewable power generation options [13]. Its widespread availability, environmental cleanliness, diverse conversion technologies, and vast capacity make it a highly attractive solution for sustainable energy production [14]. Moreover, solar energy systems are generally characterized by their low operational expenditures, negligible environmental consequences, and adaptable frameworks that facilitate their incorporation into a diverse array of applications, spanning from domestic rooftops to extensive industrial facilities [15]. However, its intermittent nature necessitates efficient capture and storage systems to maximise utilisation [16]. The effective utilization of solar energy can be realized through various technological avenues, each tailored to distinct applications and system specifications. Solar energy can be converted into usable forms through technologies like photo thermal conversion (transforming solar radiation into heat for water heating and industrial processes) [17], photosynthesis (harnessing sunlight for chemical energy) [18], and photovoltaic (PV) conversion (directly converting solar energy into electricity) [19].

Advancements in energy storage, smart grids, and hybrid energy configurations are steadily improving solar power reliability and efficiency [20], solidifying its role in the global transition to sustainable energy systems. Solar thermal systems, in particular, play a pivotal role in capturing solar energy for electricity generation, water and space heating, and industrial processes [21]. However, the intermittent nature of solar radiation remains a challenge, requiring advanced thermal energy storage (TES) technologies to ensure stable and continuous energy supply [22]. TES systems capture surplus thermal energy during peak solar illumination and discharge it when sunlight is scarce, stabilising energy output [23]. Without efficient storage, solar thermal systems face issues like energy variability, operational inefficiencies, grid instability, and limitations in large-scale deployment. By advancing TES technologies—ranging from sensible heat storage to latent heat storage using phase change materials (PCMs) and thermochemical storage—solar thermal systems can achieve greater efficiency, reliability, and cost-effectiveness, accelerating their adoption across residential and industrial sectors [24].

PCMs have become a highly effective and promising solution for TES systems, especially in solar energy applications. They are valued for their high latent heat storage capacity and their capability to maintain nearly constant operating temperatures during phase transitions [25]. Unlike sensible heat storage materials, which rely on temperature changes to store energy, PCMs excel in energy storage and retrieval through phase transitions, primarily between liquid and solid states, enabling efficient absorption and release of thermal energy [26]. They can be categorised into eutectic, organic, and inorganic types, each offering distinct thermal properties suited to various applications. However, conventional PCMs face limitations such as leakage during phase transitions, phase segregation, and low thermal conductivity, hindering their scalability in solar energy systems [26]. These challenges highlight the need for innovative approaches to enhance PCM efficiency, stability, and practicality.

To address these limitations, micro- and nano-encapsulation of PCMs has gained considerable attention [27]. Encapsulation involves enclosing PCM particles within a matrix or protective shell, improving thermal stability, preventing leakage, and enhancing heat transfer properties [27]. This process also ensures better shape stability, extended operational life, and improved compatibility with various heat transfer fluids (HTFs). The development of micro-/nano-encapsulated composite PCM-based HTFs (PCM-HTFs) represents a significant advancement in solar thermal technology, offering superior thermal conductivity, better dispersion, and increased energy storage efficiency [28]. These materials have shown great promise in applications such as concentrated solar power (CSP) plants, solar water heating, and building-integrated thermal management systems [29].

The transition towards sustainable energy systems necessitates sophisticated thermal management solutions that can effectively tackle the intermittency and storage constraints associated with solar energy. PCM-HTFs have emerged as viable candidates due to their substantial latent heat storage capacity and their proficiency in regulating thermal energy in response to variable solar input. Nevertheless, despite their inherent potential, traditional PCM-HTFs frequently encounter challenges such as inadequate thermal conductivity, phase separation, and long-term instability. While previous reviews have investigated general PCM applications or conventional HTFs, a thorough and targeted assessment of the swiftly evolving field of micro-/nano-encapsulated composite PCM-HTFs is conspicuously absent. Earlier reviews typically addressed broad PCM types, encapsulation techniques, or conventional heat transfer fluids separately, without integrating these aspects into a comprehensive analysis of composite PCM-based HTFs. This review aims to fill that gap by focusing specifically on the synthesis, thermal performance, stability, and applications of micro-/nano-encapsulated composite PCM-HTFs, especially in solar energy systems.

This review is also driven by the pressing necessity to augment the efficiency, reliability, and scalability of solar thermal energy storage systems. It is posited that the micro-/nano-encapsulation and composite structuring of PCMs could substantially ameliorate traditional performance limitations, thereby enabling PCM-HTFs to satisfy the requirements of next-generation solar technologies. Consequently, this work systematically investigates recent advancements in encapsulation methodologies, material innovations, and composite formulations, while critically assessing their impact on key performance indicators—including enhancements in thermal conductivity, cyclic stability, and overall system feasibility.

Furthermore, the review distinctively examines how these advanced materials confront enduring challenges such as intermittent solar radiation, phase segregation, and thermal degradation. By synthesizing recent breakthroughs, pinpointing existing research deficiencies, and delineating prospective research trajectories, this review serves as a timely and comprehensive resource aimed at guiding the further advancement and practical application of PCM-HTFs within sustainable energy systems.

2. Methods

This section presents a comprehensive overview of the materials and methods related to the development of composite phase change materials for thermal energy storage applications. It begins with the formulation of composite phase change materials and progresses through various encapsulation strategies, highlighting both traditional and advanced techniques. Special attention is given to the selection of shell materials, the encapsulation of different types of phase change materials (organic, inorganic, and eutectic), and the development of micro-/nano-encapsulated systems. Finally, the fundamental properties and stability of phase change slurries are discussed to support their practical application in solar thermal systems.

2.1. Composite phase change materials

PCMs can be broadly classified into three major categories based on phase transition characteristics and their compositions: organic, inorganic, and eutectic [30]. Each category exhibits distinct thermal and chemical properties, making them suitable for different solar energy applications. Organic PCMs, such as paraffin waxes and fatty acids, are widely utilised in thermal energy storage due to their abundance, chemical stability, and non-corrosive properties. They exhibit high latent heat capacity, enabling efficient energy storage. However, their low thermal conductivity limits heat transfer efficiency, resulting in slower energy absorption and dissipation, which can compromise overall system performance [31].

Inorganic PCMs, including metallic alloys [32], and salt hydrates [33], are characterised by high thermal conductivity and greater storage capacity compared to organic PCMs, rendering them ideal for high-temperature environments such as CSP systems. Salt hydrates provide high latent heat storage, while metallic alloys exhibit excellent resistance to extreme thermal stress. However, challenges such as phase segregation, subcooling, and corrosion can impair their performance, leading to thermal inconsistencies, reduced energy storage efficiency, and material degradation [34]. Eutectic PCMs are mixtures of two or more substances that melt and solidify at a constant temperature, ensuring a stable and predictable phase change process. Their primary advantage lies in their precise and narrow melting range, making them highly adaptable for diverse thermal storage applications. By carefully selecting components, their melting points can be adapted to meet distinct energy storage demands, such as those in solar systems. Additionally, eutectic PCMs can offer enhanced thermal performance, including higher latent heat and thermal conductivity. However, material compatibility and cost considerations must be addressed to optimize their use.

The integration of PCMs into solar energy systems provides notable advantages, particularly through their latent heat storage capability [35]. By absorbing and releasing substantial amounts of thermal energy during phase transitions, PCMs effectively regulate temperature fluctuations and maintain system stability. This thermal buffering enhances the performance and lifespan of solar energy components by preventing overheating and reducing the frequency of start-stop cycles in thermal systems.

PCMs also improve the overall energy efficiency of solar technologies. During periods of high solar irradiance, PCMs absorb excess heat, which can be released later when solar input decreases—minimizing reliance on auxiliary systems and smoothing energy delivery. These characteristics make them suitable for a wide range of solar applications, including passive solar heating in buildings [36], solar water heaters [37], and large-scale CSP systems [38]. Importantly, their ability to diminish energy losses and enhance energy utilization contributes to a lower carbon footprint, aligning with global goals for cleaner energy systems.

However, selecting appropriate PCMs for specific solar energy applications involves critical trade-offs [30]. For instance, organic PCMs (e.g., paraffins and fatty acids) offer excellent chemical stability, non-corrosiveness, and minimal supercooling, making them ideal for low-to medium-temperature applications like solar water heating or building integration [39]. Nonetheless, they suffer from low thermal conductivity, which impedes heat exchange efficiency. Inorganic PCMs (e.g., salt hydrates, metallic alloys) have higher thermal conductivities and latent heat values, making them attractive for high-temperature systems such as CSP systems [40]. Yet, they present challenges like phase segregation, corrosiveness, and supercooling, which can degrade long-term performance and require advanced stabilization techniques.

To overcome these limitations, various augmentation techniques have been employed, each with associated trade-offs. Microencapsulation improves shape stability and leakage prevention, especially in organic PCMs, but increases material complexity and manufacturing cost [41]. Incorporation of high-conductivity additives—such as carbon nanotubes [42], graphene [43], or metal nanoparticles [44]—boosts heat transfer rates but may also reduce latent heat capacity, increase material density, and raise concerns over long-term dispersion stability and cost.

Moreover, cost and scalability remain pressing barriers. While some organic PCMs are relatively inexpensive, the integration of nanomaterials or encapsulation techniques raises the overall cost, potentially limiting their industrial deployment [45]. Chemical stability under repeated thermal cycling is another crucial factor—many PCMs degrade or lose performance after prolonged use, necessitating materials that can withstand hundreds or thousands of cycles without significant loss of function [46].

From a systems engineering perspective, compatibility with storage containers and heat exchangers is essential [47]. Inorganic PCMs may induce corrosion in metal components, while leakage or expansion of organic PCMs can cause mechanical stress or flow blockages [48]. Therefore, practical deployment requires careful material selection not only based on thermal performance but also in relation to cost, stability, environmental impact, and system integration feasibility. In summary, the choice of PCM and enhancement method must be closely aligned with the temperature range, system design, and economic constraints of the target solar application. A holistic evaluation—considering thermal conductivity vs. latent heat trade-offs, cost vs. durability, and performance vs. integration complexity—is necessary for developing PCM-based solutions that are both technically effective and commercially viable in solar energy systems.

To address these challenges and optimise the use of PCMs in solar applications, researchers are prioritizing advanced PCM formulations, improved encapsulation techniques, and novel composite materials. The next section explores the encapsulation of PCMs, a critical strategy for enhancing their stability, efficiency, and overall performance in solar thermal energy systems. Micro- and nano-encapsulation techniques are increasingly being investigated to mitigate drawbacks such as phase segregation, leakage, and thermal conductivity limitations, ensuring PCMs remain a promising and functional solution for solar energy storage.

2.2. *Encapsulation of phase change materials*

Encapsulation of PCMs is a vital strategy to enhance their stability, improve heat transfer performance, and address challenges such as leakage and phase segregation [49]. By enclosing PCMs within a protective shell (Fig. 1), their thermal properties can be more effectively managed, resulting in greater efficiency for solar energy applications [50].

The selection of encapsulation techniques is linked to the physicochemical properties of the PCM being used—namely, whether it is inorganic, organic, or eutectic [51]. Organic PCMs, such as paraffins and fatty acids, are chemically stable and non-corrosive, making them well-suited for polymer-based encapsulation methods like suspension polymerization, interfacial polymerization, and emulsion polymerization [27]. These methods offer good control over particle size and shell thickness, which helps mitigate leakage during phase transitions. In contrast, inorganic PCMs, particularly salt hydrates and molten salts, often exhibit high thermal conductivity but suffer from phase segregation and supercooling. To address these issues, techniques such as sol–gel synthesis and in situ polymerization are commonly employed due to their ability to form robust, thermally stable shells that can withstand repetitive cycling and high operating temperatures [52]. Eutectic PCMs, which are composed of multi-component systems with specific melting behaviours, require encapsulation methods that ensure compatibility with all constituent components while preventing component separation. Methods like spray drying or microfluidic encapsulation offer precise control over encapsulant uniformity and thermal response, which are critical for preserving the phase equilibrium in eutectics [53]. Therefore, encapsulation technique selection is highly dependent on the material stability, desired shell properties, and the thermal and mechanical demands of the target application.

This section explores various encapsulation techniques, shell materials, and the encapsulation of different PCM types, highlighting their role in advancing solar thermal energy systems.

2.3. *Encapsulation techniques*

PCM encapsulation techniques can be broadly classified into three main categories: physico-chemical, physico-mechanical, and chemical methods [54] (Fig. 2). Each method offers distinct advantages and is chosen based on application-specific requirements, such as thermal stability, mechanical strength, and scalability.

Physico-mechanical methods are scalable and cost-effective however may result in inconsistencies in shell thickness [55]. Physico-chemical methods contribute greater precision in controlling the shell structure, even though they are often slower or more complex to implement [54]. Chemical methods also enable highly customized and durable encapsulation but require advanced equipment and precise control over chemical reactions [54].

The determination of a suitable encapsulation methodology is contingent upon a multitude of factors, such as the targeted application, the PCM's physicochemical characteristics, and pragmatic considerations including scalability and economic viability. Physicochemical techniques, encompassing processes like spray drying and coacervation, are mostly preferred for organic PCMs due to their comparatively low melting temperatures and compatibility with polymer matrices, providing a moderate balance between scalability and cost-effectiveness alongside acceptable encapsulation stability [53]. Physico-mechanical methodologies, exemplified by fluidized bed coating and electrospinning, are frequently utilized when mechanical integrity or structural customization is of paramount importance, even though these methods may face limitations due to additional operational complexity and diminished throughput [53]. Chemical approaches, which incorporate interfacial and in-situ polymerization, afford robust encapsulation and

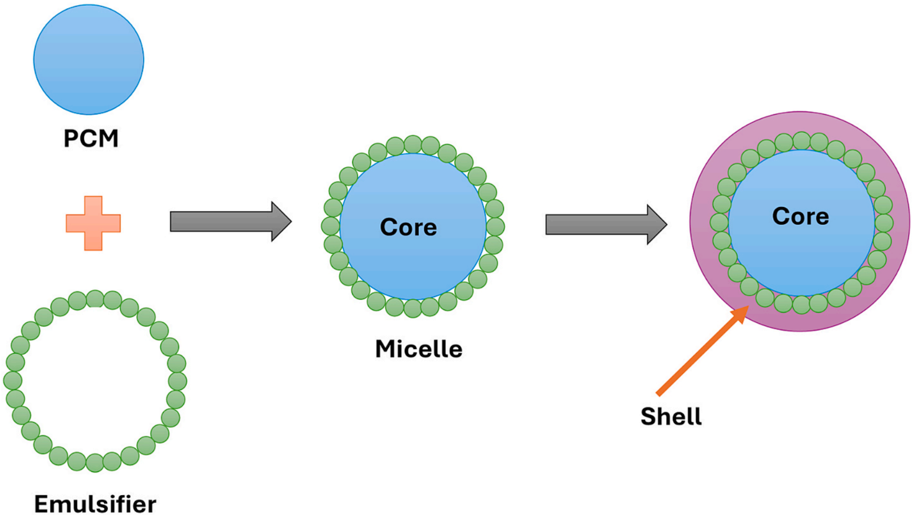


Fig. 1. Schematic of encapsulated PCM.

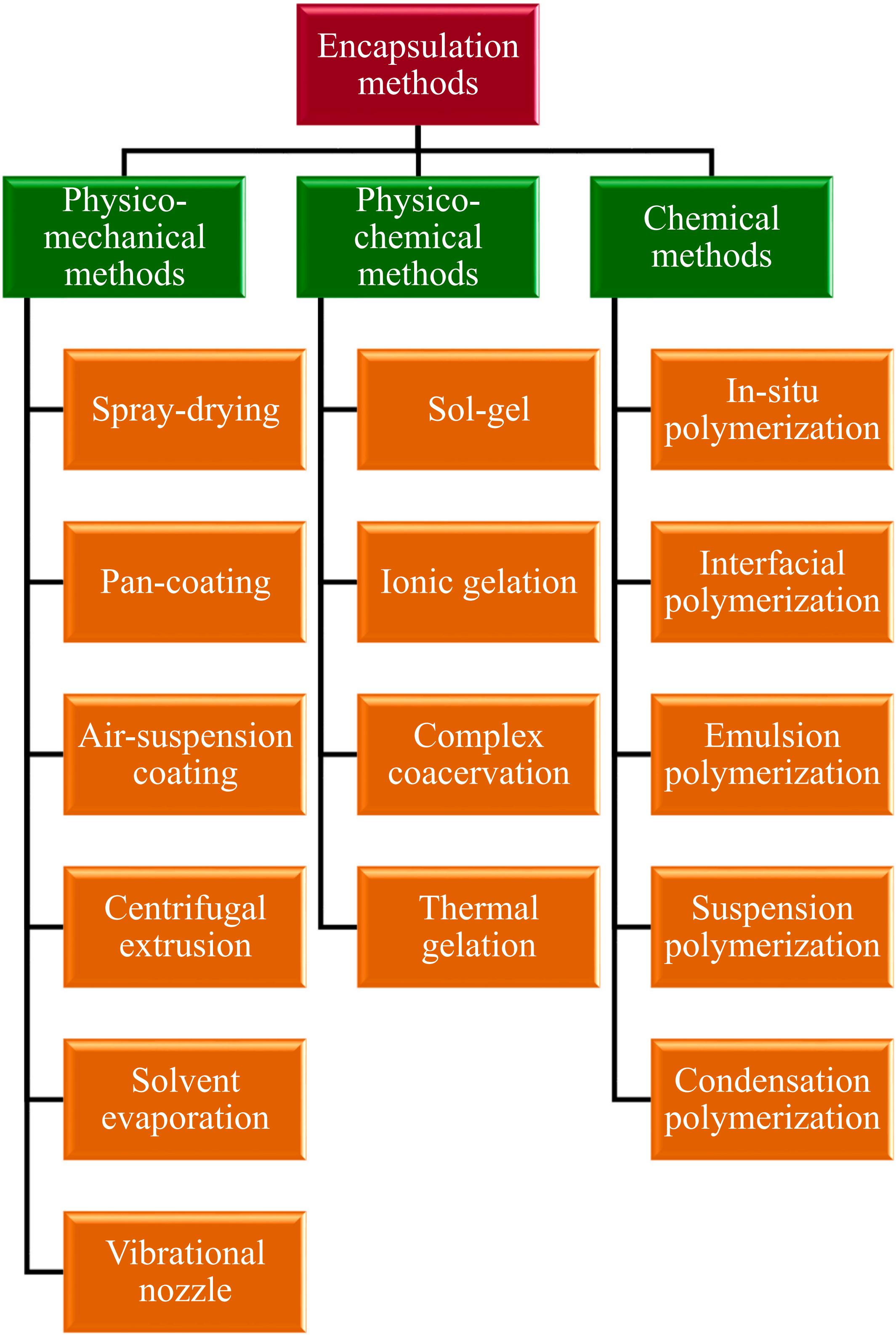


Fig. 2. Encapsulation methods of PCMs.

thermal resilience, rendering them appropriate for inorganic and eutectic PCMs that are susceptible to phenomena such as supercooling or phase segregation. Nonetheless, these techniques may entail elevated material and processing expenses and necessitate meticulous control over reaction parameters [56]. Consequently, a comprehensive assessment of thermal efficacy, shell-PCM compatibility, leakage mitigation, and production practicability is imperative when discerning encapsulation strategies tailored to diverse PCM categories and application scopes.

Each approach comes with its own set of challenges, and the selection of method is determined by the specific properties required for the encapsulated PCMs. This flexibility allows researchers and engineers to tailor encapsulation techniques to meet the demands of diverse solar energy applications.

2.3.1. Physico-mechanical methods

These methods utilise physical forces—such as spraying, fluidization, extrusion, and centrifugal forces—to create a protective shell around the core material. Spray drying is a scalable and cost-effective technique which produces uniform particles however demands precise drying control. Extrusion allows for durable, large-scale production but often requires additives for uniformity. Pan coating is simple and commonly used, even though less effective for irregular or small particles. Air-suspension coating ensures uniform coatings and high encapsulation efficiency but consumes high energy and has limited shell thickness control. Solvent evaporation offers good shell thickness control and is straightforward but involves volatile solvents and high energy use. Lastly, the vibrational nozzle method enables high encapsulation rates and is suitable for scale-up, although it requires complex equipment and offers limited control over particle uniformity [55].

They are extensively adopted due to their cost-effectiveness, scalability, and relatively straightforward processing. However, achieving uniform encapsulation often requires precise control over process parameters, which remains a significant challenge in ensuring consistent product quality. Further, whereas these techniques are well-suited for heat-stable materials and large-scale production, their applicability is limited when dealing with extremely sensitive or reactive substances. This restricts their use in advanced applications where material stability and encapsulation integrity are critical. Future research should focus on developing more robust and adaptable encapsulation methods that can maintain uniformity and stability even with sensitive core materials, potentially through novel process controls or hybrid encapsulation strategies.

2.3.2. Physico-chemical methods

These methods combine chemical reactions with physical dispersion to achieve encapsulation. They offer greater control over shell properties, often producing microcapsules with improved stability and encapsulation efficiency. Coacervation enables high encapsulation efficiency and controlled shell thickness but requires stabilizers and strict process conditions. The sol–gel process provides excellent thermal stability and chemical resistance, though it involves long processing times and costly precursors. Ionic gelation is a simple, eco-friendly method suitable for water-soluble materials, but it requires careful control of ionic strength. Thermal gelation ensures good control over shell formation with minimal chemical use however is limited by the materials involved's thermal sensitivity [57].

On the other hand, these systems typically require precise formulation adjustments and exhibit sensitivity to variations in temperature, pH, and ionic strength [53]. Such sensitivity poses challenges for maintaining consistent and reliable performance across diverse application conditions. Addressing this restriction calls for further research into adaptive encapsulation materials and robust formulations that can tolerate environmental fluctuations. Developing techniques to enhance stability under varying physicochemical conditions will be important for expanding their practical usage and augmenting long-term reliability.

2.3.3. Chemical methods

These methods utilise specific chemical interactions and bonding to create a protective shell. They offer robust encapsulation stability and protection but often demand precise control over reaction conditions. Interfacial polymerization creates strong shells with high encapsulation efficiency by facilitating reactions at the interfaces of immiscible phases, which requires precise control. Emulsion polymerization provides good particle size uniformity and high efficiency; however, it relies on surfactants and presents challenges when scaling up. Condensation polymerization produces thermally stable shells that are suitable for high-temperature PCMs, even though it can be slow and may generate by-products. Suspension polymerization leads to uniform, spherical particles and is suitable for large-scale PCM encapsulation, however it has lower efficiency when working with viscous materials and is significantly influenced by the choice of solvent and process conditions. In-situ polymerization provides excellent shell stability and integrity and, but it involves complex optimization of the reaction conditions [56].

On the other hand, their application can be constrained by high production costs and the necessity for precise compatibility between shell and core materials. These challenges not only affect economic feasibility but also limit material selection and scalability. Future research can focus on developing cost-effective synthesis methods and exploring versatile shell materials that can accommodate a wider range of core substances without compromising stability. Innovations in process optimization and material engineering are essential to overcome these barriers and enable broader commercial adoption.

2.4. Encapsulation shell materials

The choice of shell materials for PCM encapsulation is crucial in influencing the long-term durability, overall compatibility, and heat transfer performance of the PCM across different applications. The choice of material directly impacts the encapsulation's mechanical strength, thermal stability, and chemical resistance, all of which are essential for ensuring optimal PCM performance over repeated thermal cycles. Shell materials are broadly classified into three main types: inorganic, organic, and hybrid (a combination of organic and inorganic) [58] (Fig. 3).

Each category offers distinct properties and advantages, making them suitable for different temperature ranges and operational conditions in solar thermal systems. Organic shell materials, such as polymethyl methacrylate (PMMA), polylactic acid (PLA), polypropylene, polyethylene, and polyurethane offer flexibility and are easy to process. They are generally suitable for applications involving low to moderate temperatures and are often cost-effective. In the case of PLA, the material is also environmentally friendly and biodegradable. However, these organic materials usually have lower thermal stability compared to inorganic options [58].

In contrast, inorganic shell materials like magnesium oxide, alumina, silica, and zirconia exhibit outstanding thermal stability, mechanical

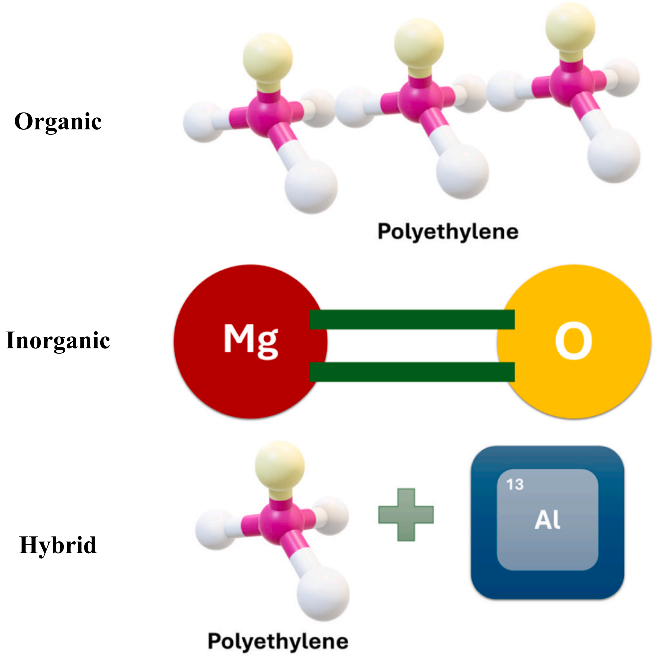
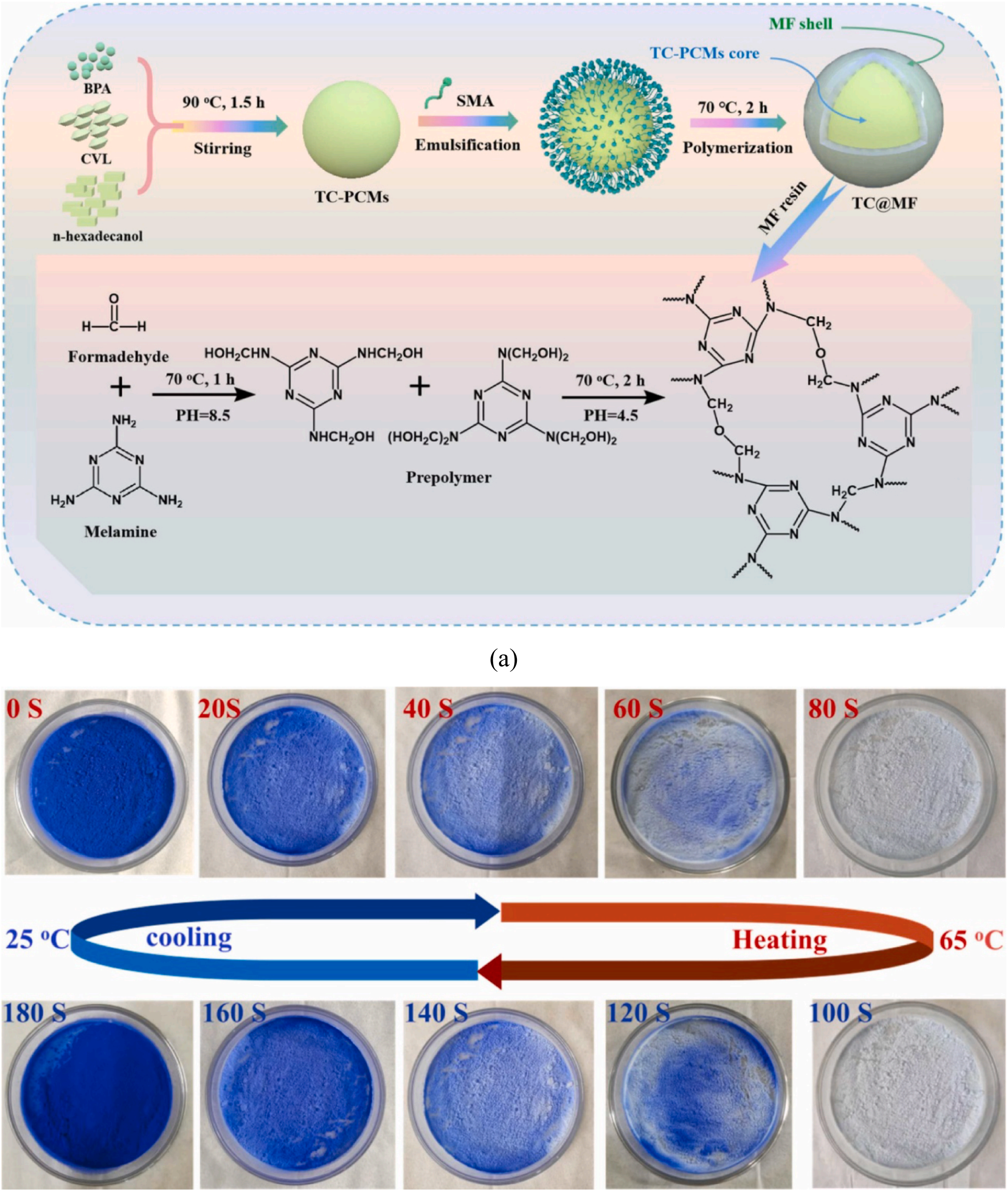


Fig. 3. Shell materials for encapsulation.

strength, and resistance to harsh environments [58]. This makes them ideal for long-term and high-temperature applications. Inorganic materials are typically chemically inert and contribute high thermal conductivity. Hybrid organic–inorganic materials combine the best properties of both types, utilizing the flexibility and ease of processing of polymers along with the high thermal resistance and strength of ceramics or metals [54]. Examples of these hybrid materials include metal-polymer, polymer-ceramic, and polymer-glass fiber composites. These combinations augment thermal conductivity, mechanical durability, and stability under changing conditions, making them specifically suitable for advanced PCM encapsulation.

2.4.1. *Organic shell materials*

Organic shell materials are commonly used in low- to medium-temperature solar thermal systems because of their affordability, flexibility, and superior processability. Commonly used organic shell



(a)

(b)

Fig. 4. (a) Schematic of the synthesis scheme and mechanism of TC@MF, and (b) reversible thermochromism digital images of TC@MF after 100 thermal cycles of heating and cooling [67].

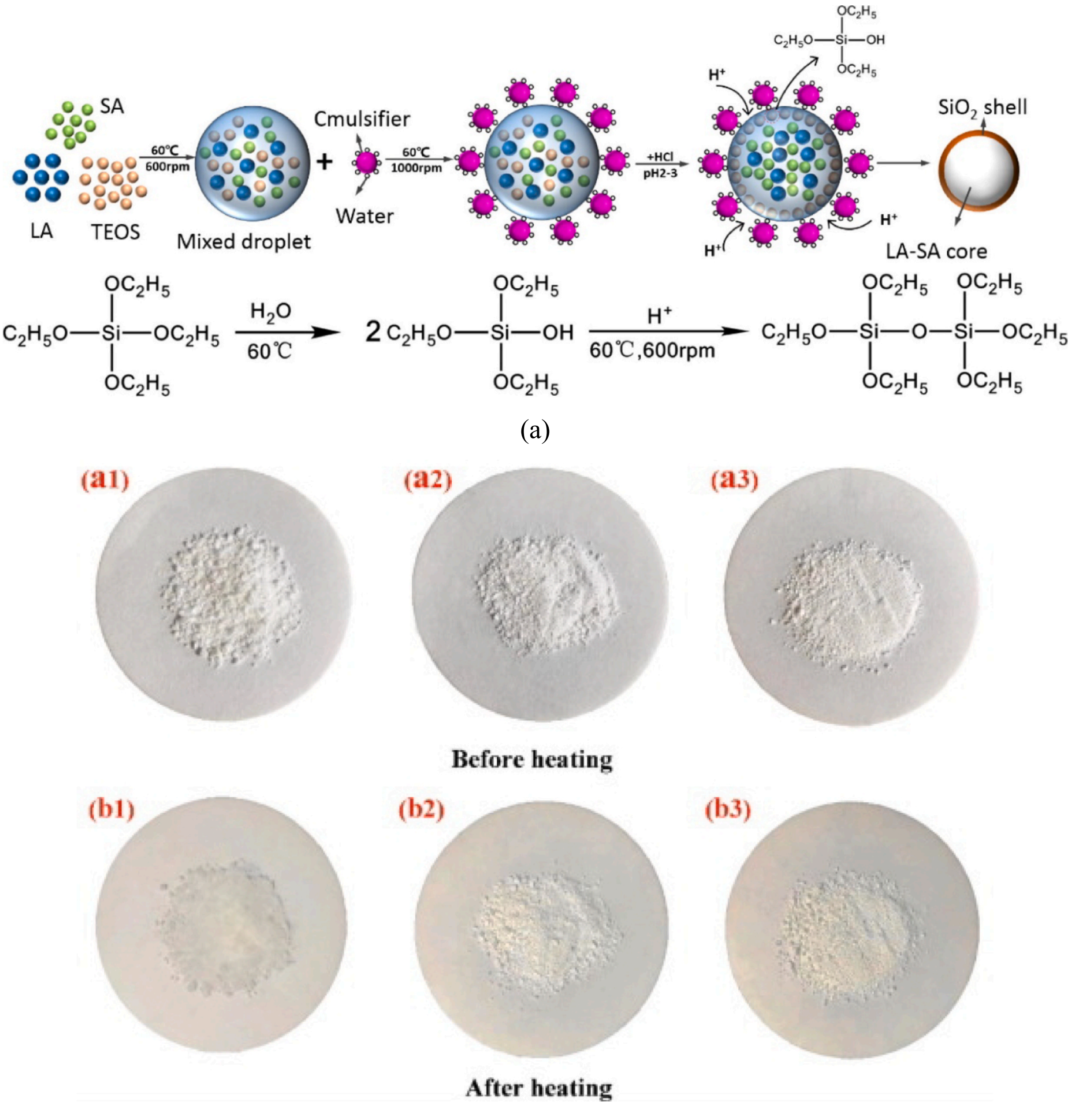
materials include urea–formaldehyde (UF) resin [59], polyurea (PU) [60], melamine–formaldehyde (MF) resin [61], acrylic resins [62], polystyrene (PS) [63], poly(urea-urethane) [64], phenolic resin [65], and polymethylmethacrylate [66].

Various organic shell materials have been extensively studied, each offering unique thermal advantages. For instance, melamine–formaldehyde resin has demonstrated exceptional thermal cycling stability, maintaining its properties over 100–200 cycles, along with high enthalpy values and thermochromic capabilities by Li et al. [67] (Fig. 4). Poly (methyl methacrylate-co-methacrylic acid) has been shown to enhance melting enthalpy (127.3 J/g) and increase thermal stability by approximately 30 °C, significantly improving heat storage performance, as reported by Mahajan et al. [68]. Additionally, Zhu et al. [69] found that PU exhibits strong film-forming ability and stable heat-storage coatings, with a latent heat capacity of 45.5 J/g and a total heat storage capacity of 151.89 J/g.

Furthermore, Ertuğral et al. [70] revealed that PMMA-based microcapsules showed good thermal stability up to 100 °C and latent heat capacity of 89.63 J/g. PU shells derived from soy polyols exhibited excellent thermal cycling stability, with 91.5 % energy storage efficiency and 91.4 J/g latent heat by Yan et al. [71]. Polyurea-based shells improved capsule compactness and reduced mass loss by less than 6 % after drying at 120 °C for 1 h, while also influencing crystallization behavior by Lu et al. [72]. Yang et al. [73] discovered that the hybrid PMMA-polyurea shell augmented cyclic and thermal stability, achieving a high encapsulation ratio of 94.5 % and a melting enthalpy of 222.6 J/g, indicating their suitability for durable and efficient PCM encapsulation in thermal energy storage systems.

2.4.2. *Inorganic shell materials*

Inorganic shell materials are commonly selected for high-temperature applications because of their mechanical robustness and



(a)

(b)

Fig. 5. (a) The preparation process of phase change microcapsules, and (b) the leakage analysis of MPCMs [86].

superior thermal stability. These materials are particularly effective in environments such as high-temperature solar collectors and solar power plants, where long-term performance under elevated temperatures is critical. Common examples include silica (SiO_2) [74], calcium carbonate ($CaCO_3$) [75], titanium dioxide (TiO_2) [76], zinc oxide (ZnO) [77], germanium dioxide (ZrO_2) [78], and aluminum hydroxide (AlOOH) [79] are typical examples of shell materials.

Recent studies have demonstrated the remarkable potential of inorganic shell materials in enhancing PCM performance. For instance, Cai et al. [80] found that lead tungstate ($PbWO_4$) exhibits excellent cycle stability and solid–liquid phase-transition reversibility, with a latent heat storage capacity exceeding 100 J/g, making it ideal for long-term thermal applications. Chen et al. [81] reported that $CaCO_3$ microcapsules feature a well-defined core–shell structure with spherical morphology, effectively regulating heat with a capacity of over 130 J/g. When combined with magnetite (Fe_3O_4), $CaCO_3$ not only increased phase-change enthalpy (exceeding 120 J/g) but also enhanced thermal conductivity by over 400 %, achieving an impressive photothermal conversion efficiency of 95.08 % [82]. Additionally, Hou et al. [83] demonstrated that TiO_2-based composite capsules exhibit outstanding thermal durability and phase-change reversibility after 100 cycles, retaining 98.08 % of their storage capacity and achieving a photothermal conversion efficiency of 78.4 %.

SiO_2-based shell materials have been widely investigated for PCM encapsulation due to their excellent thermal properties. Do et al. [84] reported that SiO_2 microcapsules demonstrated high thermal conductivity and an encapsulation efficiency of 61.48 %, indicating superior heat transfer performance. Tan et al. [85] showed the SiO_2-encapsulated PCMs' long-term thermal stability, maintaining performance after 300 heat-release and heat-absorption cycles. Similarly, Wang et al. [86] investigated that SiO_2 capsules provided efficient temperature regulation and heat storage abilities, with negligible change in latent heat even after 300 freezing/melting cycles (Fig. 5). Moreover, Jing et al. [87] developed SiO_2/Fe_3O_4 composite shells, which exhibited enhanced shape stability, excellent phase-change reversibility, and robust thermal cycling stability. These composite capsules' phase-change enthalpies ranged from 46.8 to 115.7 J/g, demonstrating their potential for high-performance thermal energy storage applications.

These findings emphasize the significant potential of inorganic shell materials in augmenting the encapsulated PCMs' performance for photo thermal conversion and thermal energy storage applications. However, challenges such as potential chemical incompatibility with certain PCMs, brittleness, and difficulties in large-scale fabrication remain. Future research should focus on optimizing fabrication methods to enable cost-effective, scalable production will be critical to fully realize their practical applications.

2.4.3. *Organic-inorganic hybrid shell materials*

Hybrid shell materials combine the strengths of both inorganic and organic components, offering a unique balance of flexibility, high thermal conductivity, and mechanical strength. These materials are especially suitable for medium- to high-temperature solar thermal systems, including CSP systems and advanced solar collectors. Examples of hybrid shell materials include MF/SiO_2 [88], $PMMA/BN/TiO_2$ [89], poly(methyl methacrylate-co-methyl acrylate) (P(MMA-co-MA)) with Al_2O_3 [90], $PMMA/Si_3N_4$ [91], poly(methyl methacrylate-*co*-butyl acrylate) with TiO_2 [92], PUA/TiO_2 [93], paraffin wax with St-DVB-SiO_2 hybrid shells [94], polystyrene/graphene oxide [95], $PMMA/SiO_2$ [96,97], poly(melamine–formaldehyde)/silicon carbide [98], PU/Fe_3O_4 [99], $PMMA/TiO_2$ [100], $PMMA/TiO_2$ [101], polymer-SiO_2/TiC [102], PU/Fe_3O_4 [103], and SiO_2/polymer [104].

Recent studies have demonstrated the exceptional performance of hybrid shell materials in enhancing PCM-based energy storage systems. For instance, $PMMA/SiO_2$ hybrid shells significantly reduced leakage rates while maintaining excellent heat storage and release capabilities, achieving an enthalpy of 156.6 J/g, making them highly promising for thermal energy storage applications [105]. The incorporation of TiO_2 nanoparticles into MF shells improved thermal stability, prevented supercooling, and enhanced rupture load capacity by up to 138.14 % [106]. Similarly, MF/TiO_2 composite capsules exhibited a 30.4 % improvement in rupture strength and a 17.2 % increase in tensile strength compared to conventional MF-based capsules, further highlighting their mechanical durability [107]. Additionally, aluminum nitride (AlN) was shown to significantly boost thermal conductivity—17.5 times higher than that of pure PCM—while maintaining a substantial latent heat capacity of 116.26 kJ/kg during melting and 115.96 kJ/kg during solidification, underscoring its potential for high-performance thermal management systems [108].

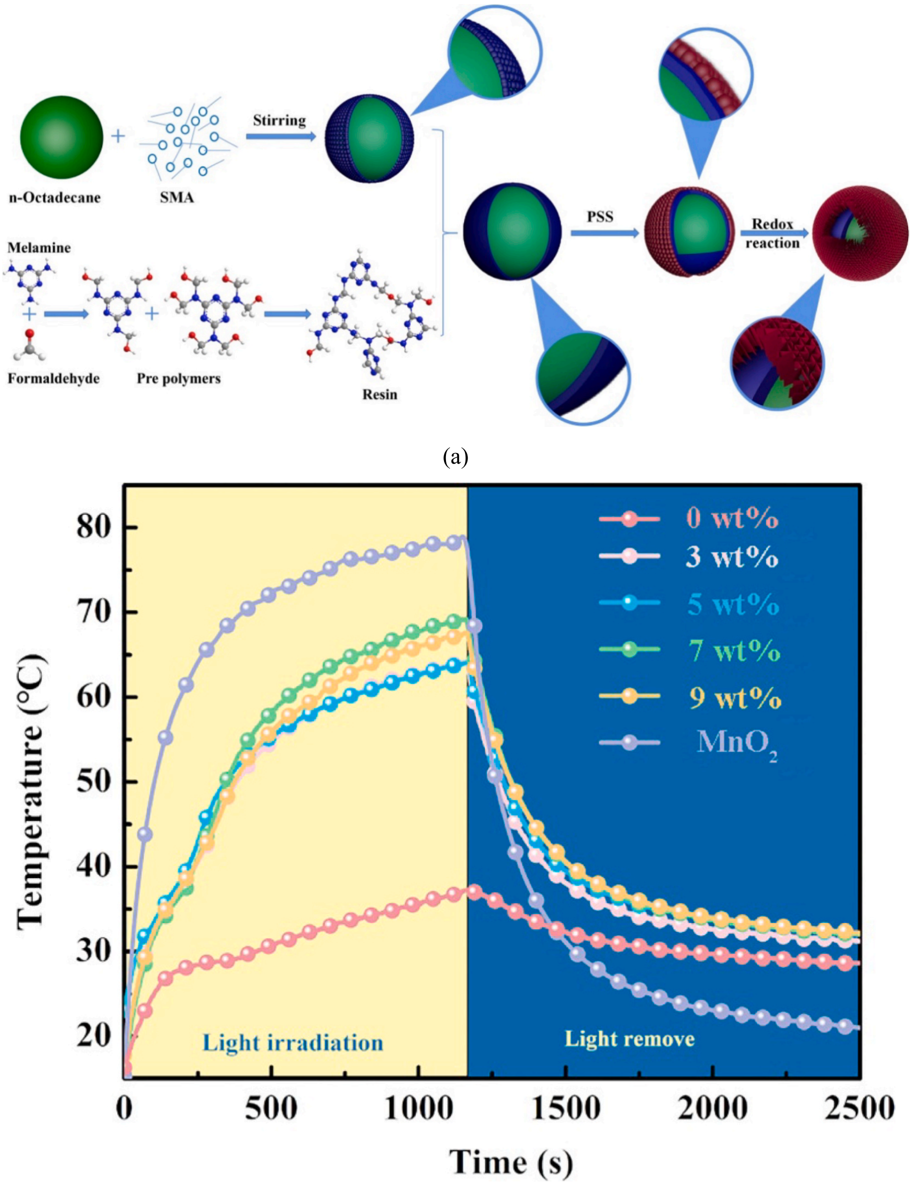
Several advanced composite and hybrid shell materials have indicated remarkable performance in encapsulating PCMs. Wang et al. [109] investigated melamine–urea–formaldehyde (MUF) combined with TiO_2 and found that the resulting nanocapsules displayed high chemical and thermal stability, with a melting enthalpy of 156.2 J/g, an encapsulation ratio of 68.6 %, and a decomposition temperature of 155.36 °C. Jiang et al. [110] reported on a polymer–SiO_2 composite PCM that showed better reusability, improved thermal conductivity, magnetic responsiveness, and a high photo thermal conversion efficiency of 93.9 %. Han et al. [111] also developed a MF shell doped with manganese dioxide (MnO_2), which relatively augmented light-to-heat conversion and thermal storage capabilities, achieving a phase change enthalpy between 133.56 and 152.71 J/g (Fig. 6). Zhang et al. [112] explored an MF/cadmium sulfide hybrid shell, which maintained a stable phase change enthalpy of 114.58 J/g even after 100 thermal cycles and reached a photo thermal conversion efficiency of 91.3 %, emphasizing its durability and energy conversion potential.

These findings underscore the significant advantages of hybrid and composite shell materials in improving thermal conductivity, mechanical stability, and overall efficiency in PCM-based energy storage systems, making them a key area of focus for advancing solar thermal technologies.

2.5. *Encapsulation of organic phase change materials*

Organic PCMs, such as capric acid [113], paraffin wax [114], n-octadecane [115], PEG-6000 [116], hydroxystearic acid [117], 1-dodecanol [118], butyl stearate [119], lauryl alcohol [120], n-hexadecane [121], propyl palmitate [122], PEG-8000 [123], n-heptadecane [124], are extensively used due to their high latent heat capacity and chemical stability. Encapsulation further prevents leakage during phase transitions and enhances their heat transfer efficiency.

For n-octadecane, Jin et al. [125] reported that the composite structure increased the latent heat capacity of the suspension, with values of 8.47, 16.95, and 25.46 J/g for capsule concentrations of 5, 10, and 15 wt%, respectively. However, thermal conductivity decreased by 13.71 % at 15 wt% capsule content compared to the pure suspension. For n-hexadecane, Parvate et al. [121] demonstrated that the composite PCM exhibited a well-defined spherical core/shell structure with a TiO_2-modified poly(4-MeS-co-DVB) shell. After 100 thermal cycles, the encapsulation efficiency reached 76.6 %, with a phase change enthalpy of 174 J/g, highlighting its excellent stability and performance. In the case of paraffin wax, Liu et al. [126] found that the encapsulated PCM offered enhanced heat storage, UV absorption, and improved thermal conductivity. The composite also significantly reduced the supercooling degree to 1.00 ± 0.08 °C, which was 3.41 °C lower than that of pure paraffin wax. For n-octadecane, Zhao et al. [127] observed that the microcapsules exhibited a spherical shape with a smooth surface, high dispersibility, and no defects. The encapsulation efficiency was 51.4 ± 0.7 %, with a melting enthalpy of 111.5 ± 0.7 J/g. Lastly, for stearic acid, Li et al. [128] reported that the composite achieved impressive latent heat values of 95.76 J/g and 96.04 J/g for melting and cooling, respectively (Fig. 7). The thermal conductivity of the capsule was augmented by 90.9 % compared to pure stearic acid, significantly



(a)

(b)

Fig. 6. (a) Synthesis mechanism of the MnO_2-decorated double-shell microencapsulated PCMs, and (b) temperature–time curves of the MnO_2-decorated double-shell microencapsulated PCMs with different MnO_2 shell content [111].

improving its thermal management capabilities. Table 1 summarises recent studies on encapsulated organic PCMs, highlighting their key findings and performance metrics.

2.6. Encapsulation of inorganic phase change materials

Inorganic PCMs, such as KOH [113], $LiClO_3{\cdot}3H_2O$ [134], $Na_2HPO_4{\cdot}12H_2O$ [135], $LiNO_3{\cdot}3H_2O$ [136], $Na_2CO_3{\cdot}10H_2O$ [137], $FeBr_3{\cdot}6H_2O$ [138], $CaCl_2{\cdot}12H_2O$ [139], $NaNO_3$ [140], KNO_3 [141], are valued for their substantial thermal energy storage capacity and high thermal conductivity. However, their susceptibility to phase segregation and supercooling necessitates encapsulation techniques like sol–gel synthesis and interfacial polymerization to enhance their performance.

Zhang et al. [142] demonstrated that sodium acetate trihydrate ($CH_3COONa{\cdot}3H_2O$) with a 1.0 mm thick shell effectively prevented leakage during phase transformation. The composite maintained stability, showing only a 5.13 % reduction in latent heat after 100 thermal cycling. For metallic Sn, Lu et al. [143] found that $Sn@SiO_2$-O_2 and $Sn@SiO_2\_N_2$ composites exhibited excellent durability after 100 thermal cycling, with latent heat values of 56 and 58 J/g, respectively, and a consistent melting point of 233 °C for both composites. Dey et al. [144] investigated salt hydrates and reported that PCM release was minimized to less than 10 % after one month, with no release observed after five days of immersion, indicating robust encapsulation performance. In the case of calcium chloride hexahydrate, Dey and Ganguly [145] used scanning electron microscopy to reveal capsules with a unimodal size distribution (average diameter of 978 ± 75 μm) and uniform shell thickness. Differential scanning calorimetry further demonstrated the capsules' heat release and absorption capabilities, which varied with shell thicknesses of 1.57, 4.05, and 12.8 μm. Lastly, Ping et al. [146] studied $Na_2HPO_4{\cdot}12H_2O$ and found that nanoencapsulation significantly improved the composite's thermal stability and shape, effectively preventing leakage and water evaporation during phase transformation.

Calcium chloride hexahydrate (CCHH) exhibited augmented thermal stability when 75 % of CCHH was dispersed as droplets between 100 and 300 μm in size, with melting and crystallization heats of approximately

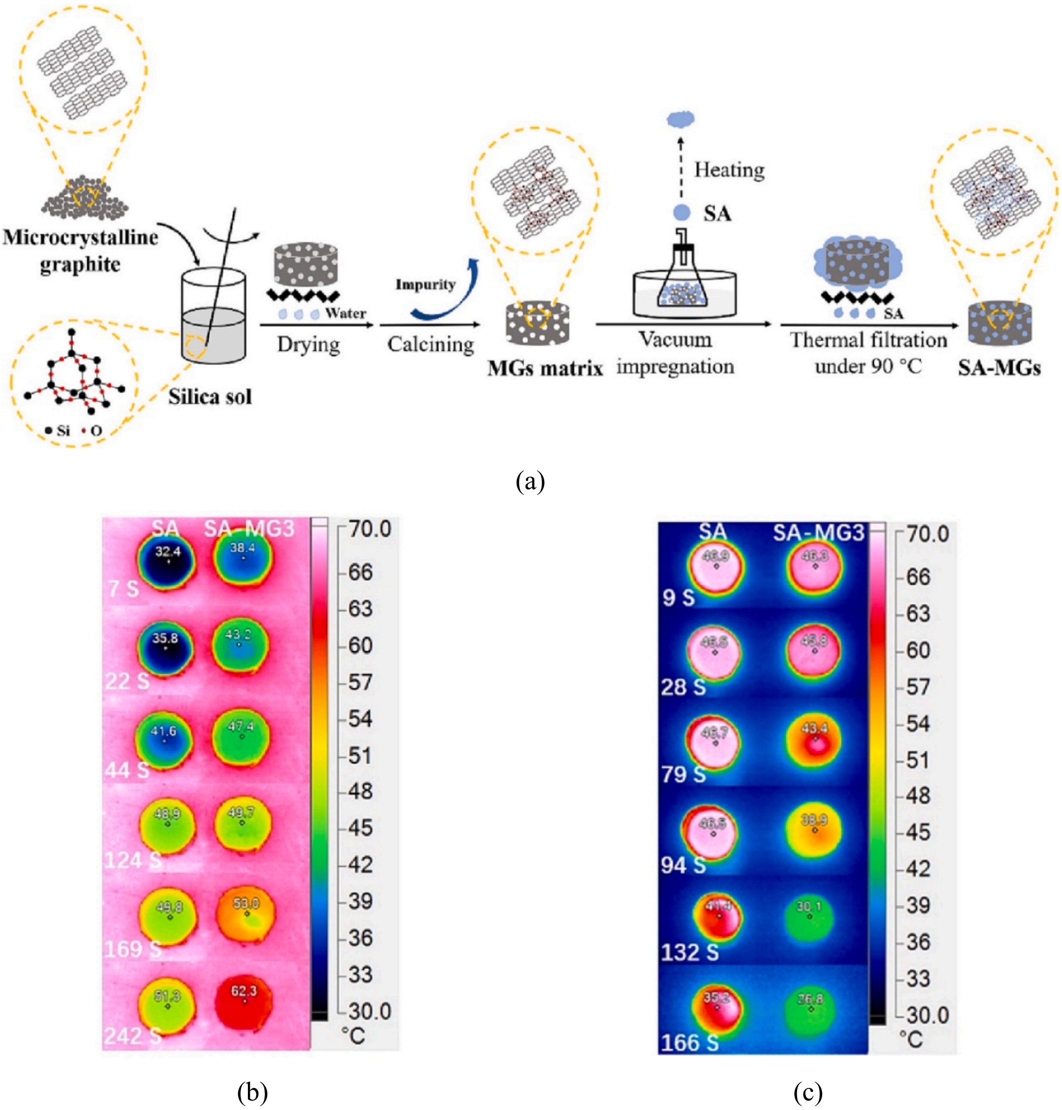


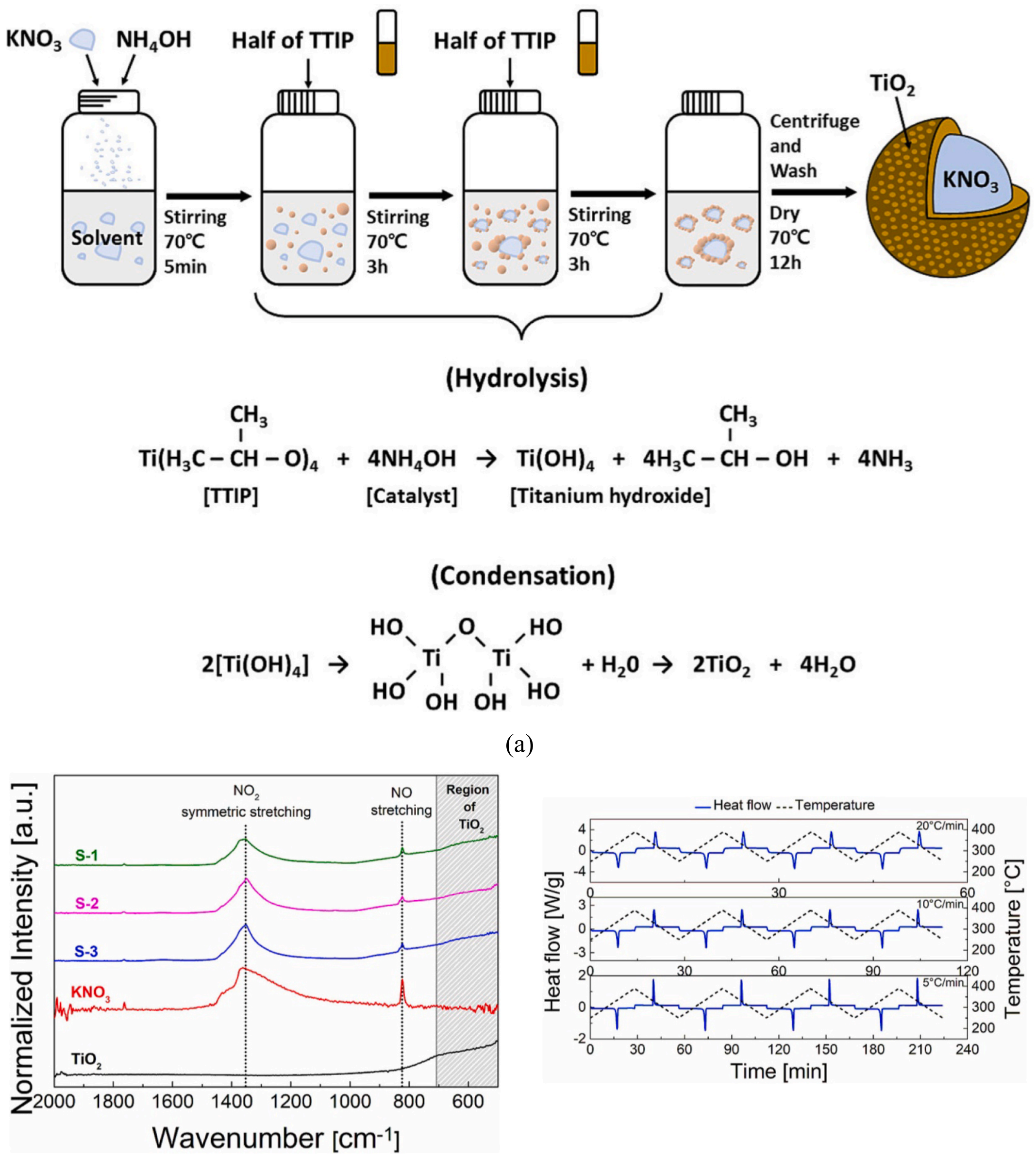
Fig. 7. (a) Preparation schematic for composites by vacuum impregnation method, thermal infrared camera images of (b) SA and SA-MG3 during heating, and (c) SA and SA-MG3 during cooling [128].

Table 1
Encapsulated organic PCMs and key findings.

Core materials	Key findings	References
n-docosane	Enhanced thermal conductivity by 471 %, high latent heat (>170 J/g).	Chen et al. [129]
Hexadecane, butyl stearate, caprylic acid	Improved thermal stability using barium-crosslinked pectin; melting enthalpies: 184.89 (hexadecane), 116 (butyl stearate), 118 (caprylic acid) kJ/kg respectively.	Reddy et al. [130]
1-dodecanol	Excellent stability after 500 cycles; latent heat ~ 169.45 J/g, encapsulation rate ~ 88.56 %.	Singh et al. [131]
Polyethylene glycol (PEG)	Maintained enthalpy (~155.8 J/g) post-encapsulation with silica shell.	Zahir et al. [132]
Stearyl alcohol	Improved thermal stability; latent heat 137.7 J/g, onset melting at 42 °C.	Chinnasamy et al. [133]

120 J/g and 160 J/g, respectively. The addition of a 3 wt% nucleating agent significantly diminished the degree of supercooling from 43 °C to 14 °C, with average crystallization and melting temperatures of 20 °C and 34 °C, respectively (Rosen et al. [147]). Sn particle-based composite PCMs featuring thermal expansion voids displayed superior thermal reliability. Incorporation of 0.8 % nano-cobalt led to a 12.6 % enhancement in thermal conductivity (Lei et al. [148]). For molten salt-based PCMs, potassium nitrate (KNO_3) composites maintained reliable thermal performance at temperatures up to 400 °C, and their thermal conductivity was augmented by 9.9 % at 25 °C (Park and Jo et al. [149], Fig. 8). Sodium nitrate ($NaNO_3$) capsules also doped with MXene displayed a distinguished augmentation in thermal conductivity and photo thermal conversion efficiency—156.2 % and 169.4 %, respectively—and maintained a thermal reliability of 94.0 % after 50 heating/cooling cycles (Mo et al. [150]). Lastly, sodium acetate trihydrate (SAT), modified using disodium hydrogen phosphate dodecahydrate, ethylene glycol, and urea, demonstrated good thermal stability, with its latent heat reducing by only 1.8 % to 130.3 J/g after 100 melting/freezing processes (Zhang et al. [151]).

Despite their superior thermal properties, salt hydrates commonly suffer from critical problems in long-term cyclic performance [52]. Issues such as supercooling, phase segregation, and dehydration during repeated solidification and melting cycles lead to a gradual reduction in latent heat capacity and reduced thermal reliability. Phase segregation compels the hydrate and anhydrous phases' separation, resulting in incomplete phase change and loss of thermal energy storage efficiency [152]. To address these challenges, recent studies have focused on



(a)

(b)

(c)

Fig. 8. (a) Schematic of synthesis processes and shell-formation mechanism of $KNO_3@TiO_2$ microcapsule, (b) fourier transform infrared spectrometry spectra of $KNO_3@TiO_2$ microcapsules (S-1, S-2, S-3), pure KNO_3, pure TiO_2 nanoparticles, and (c) heat flow curves of T-7 microcapsule for different ramp rate (5, 10, and 20 °C/min) [149].

several strategies: the utilization of nucleating agents like disodium hydrogen phosphate dodecahydrate to diminish supercooling; the development of robust encapsulation shells that minimize PCM leakage and water evaporation; and the incorporation of additives such as and urea and ethylene glycol to enhance hydro-stability and impede phase separation [153]. While these approaches have displayed augmentations in cyclic stability, they often introduce complexities in synthesis and may increase costs. Thus, ongoing research is needed to develop advanced encapsulation materials and composite formulations that combine improved thermal conductivity, anti-segregation properties, and structural integrity. Additionally, cost-effective and scalable manufacturing techniques are crucial to enable widespread deployment of salt hydrate PCMs in high-temperature solar thermal energy storage and other applications requiring durable PCMs.

These findings underline the crucial role of encapsulation in overcoming the inherent limitations of inorganic PCMs, such as suboptimal thermal conductivity and leakage during phase change, thereby enabling their effective utilization in high-performance thermal energy storage systems. Nonetheless, challenges remain in achieving long-term structural stability and minimizing thermal degradation under repeated cycling. Future research should discover advanced encapsulation techniques and novel shell materials that enhance thermal conductivity and durability while diminishing production costs, to augment the practical viability.

2.7. *Encapsulation of eutectic phase change materials*

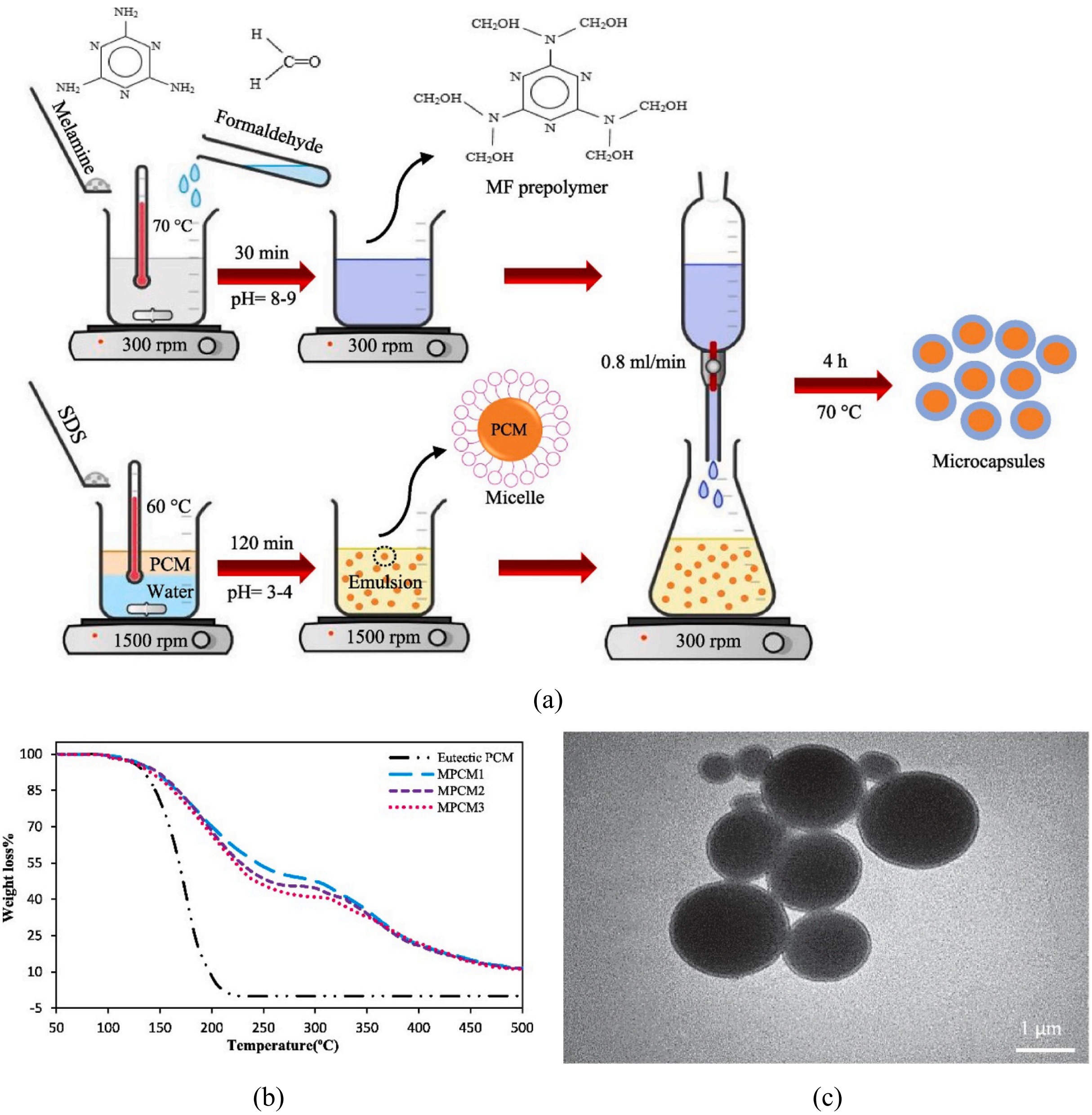
Eutectic PCMs, such as Octadecane-docosane [154], capric acid-palmitic acid-stearic acid [155], octadecane-heneicosane [118], $MgCl_2\cdot 6H_2O$-$Mg(NO_3)_2\cdot 6H_2O$ [156], $CaC_{l2}\cdot 6H_2O$-8 wt% $Mg(NO_3)_2\cdot 6H_2O$ [157], $Na_2SO_4\cdot 10H_2O$ and $Mg(NO_3)_2\cdot 6H_2O$-$Na_2SO_4\cdot 10H_2O$ [158], Li_2CO_3-Na_2CO_3 [159], myristic acid-palmitic acid eutectic [160]. Their encapsulation typically involves a combination of polymeric and inorganic shell materials to enhance thermal stability and prevent component separation.

Huo et al. [161] investigated $Na_2SO_4{\cdot}10H_2O$-$Na_2HPO_4{\cdot}12H_2O$ and found that the encapsulated eutectic hydrated salt exhibited excellent thermal reliability, with a heat storage capacity of 178.36 J/g, a latent heat of 218.58 J/g, a phase change temperature of 29.3 °C, and a supercooling degree of 4.2 °C. Rostamian et al. [162] studied eutectic fatty acids and reported that the capsules had a well-defined spherical core/shell structure, achieving a maximum encapsulation ratio of 73.26 % when the core–shell ratio was maintained at 2:1 (Fig. 9). Yao et al. [163] explored $LiNO_3$-NaCl composites and observed a significant improvement in thermal conductivity, which increased from 0.58 to 0.95 W/(m·K), representing a 63.79 % enhancement. The latent heat per unit mass and per unit volume were recorded as 117.9 J/g and 237.1 J/cm^3, respectively, marking increases of 15.48 % and 56.72 % compared to the unmodified material. Ma et al. [164] examined the octanoic acid (OA)-tetradecane (TD) system and found that the enthalpy of the exothermic phase transition increased by 67.6 % compared to TD alone, with improvements of 10.7 % and 67.6 % relative to OA and TD, respectively. Lastly, Zhou et al. [165] studied an Al-Cu composite and reported its exceptional thermal cycling behaviour and tunable melting point, ranging from 549 °C to 592 °C. The capsule demonstrated excellent thermal stability, with only a 0.09 % reduction in heat storage after 100 cooling-heating cycles.

These findings highlight the potential of encapsulated eutectic PCMs in providing customized thermal properties, enhanced stability, and improved performance for advanced thermal energy storage systems. Table 2 provides a summary of recent studies on encapsulated eutectic PCMs, highlighting their key advancements and applications.

2.8. *Micro-/nano-encapsulated phase change materials*

PCM-HTFs represent an innovative class of advanced thermal fluids that incorporate encapsulated PCMs into conventional carrier fluids [170], These hybrid fluids offer a promising solution in solar thermal systems for efficient thermal energy management by leveraging the high latent storage capacity of PCMs. This integration enhances TES and



(a)

(b)

(c)

Fig. 9. (a) schematic presentation of preparation of microcapsules, (b) thermogravimetric analysis curves of eutectic PCM and MPCMs, and (c) transmission electron microscope images of MPCM3 [162].

Table 2
Recent studies on eutectic PCMs and key findings.

Core materials	Key findings	References
Na_2CO_3-K_2CO_3	Thermal conductivity improved by 16.27 % (from 1.66 to 1.93 W/m·K); latent heat loss reduced by 4.1 % compared to pure eutectic.	Zhang et al. [166]
$H_2C_2O_4 \cdot 2H_2O$-$NH_4Al(SO_4)_2 \cdot 12H_2O$	Enhanced thermal conductivity, shape stability, and thermal properties; phase change enthalpy of 168.5 J/g at 54.10 °C.	Liao et al. [167]
Decanoic acid (CA)-dodecanol (DA)	Melting and freezing points at 24.31 °C and 26.48 °C; enthalpies of − 150.64 J/g (melting) and 197.40 J/g (freezing).	Cai et al. [168]
Sodium sulphatedecahydrate (SSD) - sodium phosphate dibasic dodecahydrate (SPDD)	Absorbance improved by 833 % (0.09 to 0.84); melting enthalpy increased to 218.1 J/g with energy storage efficiency of 71.7 %.	Kalidasan et al. [169]

enables controlled heat dissipation, significantly improving the reliability and performance of solar energy applications [171].

Encapsulation performs a pivotal role in ensuring the stability and functionality of PCM-HTFs. It prevents PCM leakage during melting, enhances thermal cycling durability, and mitigates challenges such as phase segregation and supercooling. Additionally, the material selection of encapsulation critically impacts the mechanical stability, thermal conductivity, and chemical compatibility of PCM-HTFs. Core-shell micro- and nano-encapsulation techniques further improve dispersion stability and facilitate better interaction between PCM particles and the carrier fluid (Fig. 10), resulting in more efficient heat absorption and release.

These advancements position PCM-HTFs as a transformative technology for optimizing thermal energy management in solar systems, paving the way for more efficient and sustainable energy solutions.

The integration of PCM-HTFs into solar thermal systems offers several key benefits. They improve thermal regulation by minimizing temperature fluctuations, enhancing system efficiency, and preventing overheating or degradation. PCM-HTFs also boosts heat transfer rates by increasing the working fluid's thermal capacity, optimizing heat storage and retrieval. Additionally, they enhance the energy density of TES systems, enabling more compact and lightweight designs, ideal for space-constrained applications like CSP plants, solar water heating, and photovoltaic/thermal (PV/T) systems.

Encapsulation is critical for PCM-HTFs, preventing PCM coalescence (Fig. 11), ensuring system integrity, and enhancing cyclic stability. Effective encapsulation allows PCMs to undergo repeated phase transitions without leakage or performance loss, which is vital for practical applications. Advanced techniques, such as polymeric shell encapsulation, in-situ polymerization, sol–gel processes, and hybrid organic–inorganic methods, have been broadly explored to optimize performance. Incorporating high-conductivity nanoparticles (e.g., graphene, carbon nanotubes, and metallic oxides) further improve thermal transport properties, making PCM-HTFs more effective for heat transfer. This section provides a detailed analysis of phase change slurries (PCSs) and their stability, which are essential for assuring the efficiency and durability of PCM-HTFs in real-world applications.

2.8.1. *Basic characteristics of phase change slurries*

PCSs are biphasic suspensions consisting of micro-/nano-encapsulated PCMs dispersed in a base fluid. These advanced thermal fluids combine the advantages of latent and sensible heat storage, offering significantly higher energy storage densities, improved heat transfer efficiency, and dynamic thermal regulation. The encapsulated PCMs undergo phase transitions within the suspension, enabling efficient thermal energy absorption and release while maintaining fluid stability.

The performance of PCSs depends on the encapsulation material, the properties of the encapsulated PCM, and the suspension's stability. Micro- and nano-encapsulation techniques are critical for preventing agglomeration, leakage, phase separation, and ensuring long-term thermal and mechanical stability. Additionally, the encapsulation shell material must provide sufficient chemical compatibility, structural integrity, and thermal conductivity with both the base fluid and the PCM core. PCSs have gained significant attention for applications such as electronic device cooling, district heating and cooling systems, solar thermal energy storage, and industrial waste heat recovery. Their ability to deliver precise temperature control and mitigate thermal fluctuations makes them ideal for applications requiring high thermal stability and efficiency. Table 3 summarizes the key characteristics of PCSs, highlighting their potential for advanced thermal management solutions.

The PCS's successful implementation depends on optimizing key factors such as carrier fluid viscosity, encapsulant integrity, and particle size distribution. Whilst an optimal particle size distribution augments uniform dispersion and heat transfer efficiency, it remains challenging to maintain stability over extended operation due to sedimentation. Encapsulant integrity is crucial to ensure long-term durability and hinder PCM leakage, yet many current encapsulation materials degrade over repeated thermal cycling, limiting their lifespan. Moreover, managing the carrier fluid's viscosity includes a trade-off between pumping efficiency and thermal performance, which becomes increasingly complex at higher PCM concentrations. These restrictions underscore the need for further research into smart encapsulants with self-healing or adaptive properties, nano-engineered particles to improve dispersion stability, and rheological modifiers that enable tunable flow characteristics. Addressing these challenges will be critical for realizing the PCS's full potential in high-performance heat transfer and thermal energy storage systems.

2.8.2. *Stability of phase change slurries*

The stability of PCSs is critical for their long-term performance and applicability. Key factors influencing stability include encapsulation robustness, particle dispersion, and cyclic durability. Strong encapsulation prevents PCM leakage and degradation, while effective dispersion techniques reduce agglomeration and sedimentation. Cyclic durability, validated through thermal stability testing, is essential for maintaining

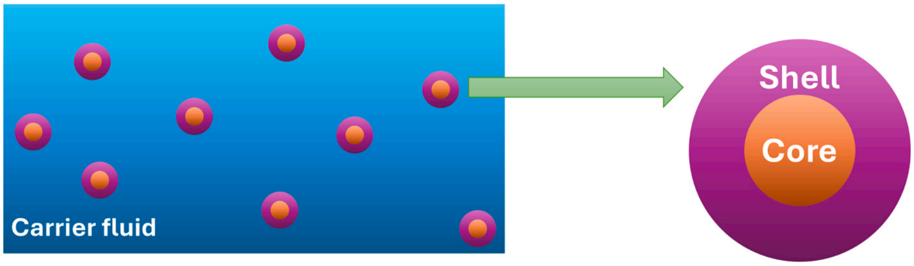


Fig. 10. Composite PCM and PCM-HTF.

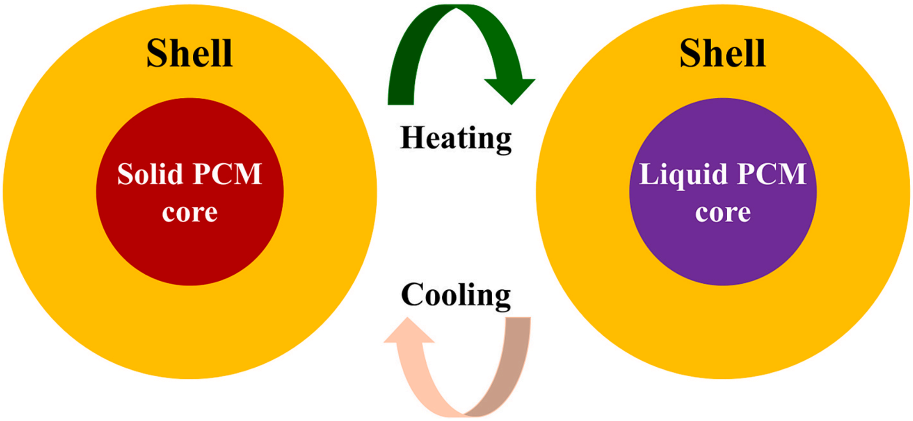


Fig. 11. Phase transformation of encapsulated PCM.

Table 3
Key characteristics of PCSs [172].

Property	Description
High thermal energy storage density	PCSs store and release latent heat efficiently, enhancing energy retention and thermal response.
Temperature stabilization	PCMs buffer temperature changes, promoting thermal stability in solar systems.
Adjustable thermophysical properties	Composition and additives can be tuned to optimize thermal conductivity, viscosity, and specific heat.
Enhanced compatibility with heat exchangers	Designed to reduce fouling and ensure effective heat transfer within system components.
Environmental sustainability	Many PCMs are bio-based and eco-friendly, combining efficiency with low environmental impact.
Precise phase transition control	Eutectic formulations enable precise melting/freezing points for adaptable operation.
Improved heat transfer coefficient	High-conductivity additives (e.g., graphene, metals) enhance overall thermal conductivity.
Shear stability and pumpability	Optimized rheology ensures stable flow and prevents pressure drops during circulation.

efficiency in high-temperature applications like solar thermal systems. Addressing these challenges with advanced encapsulation materials, optimized fluid formulations, and nanomaterial integration will enhance the practicality of PCSs for sustainable energy solutions. Table 4 outlines the primary stability considerations for PCSs.

Table 4
Stability considerations for PCSs [172].

Stability Factor	Description
Encapsulation structural integrity	Strong, stable shells (e.g., hybrid or ceramic) resist mechanical and thermal degradation over cycles.
Rheological optimization	Balanced viscosity ensures efficient flow and heat transfer without excess energy demand or loss in storage.
Thermal cycling resistance	Durable materials like silica or metal oxides prevent damage from repeated heating/cooling.
Sedimentation and colloidal stability	Dispersants and surfactants maintain stable suspension, preventing particle settling and separation.
Minimization of supercooling effects	Nucleating agents or eutectic blends improve phase change consistency and reduce supercooling.
Chemical and thermal compatibility	PCMs must resist corrosion and remain stable with system components; stabilizers and coatings help ensure this.
Long-term leakage prevention	Shape-stabilized and core–shell PCMs prevent leakage and maintain system performance.
Hybrid encapsulation approaches	Multi-layered shells improve mechanical strength, thermal performance, and chemical resistance.

3. Results and discussion

This section explores the practical applications, performance benefits, and limitations of phase change slurry-based heat transfer fluids in solar energy systems. Emphasis is placed on their roles in enhancing thermal regulation and storage efficiency across different solar technologies, including heaters, photovoltaic/thermal systems, energy storage units, and collectors. Additionally, the techno-economic and environmental impacts of integrating phase change slurries into solar systems are critically assessed. The section concludes by identifying current challenges hindering widespread implementation and outlining key recommendations for future research directions.

3.1. Applications of phase change slurries in solar systems

PCS technology, which integrates micro- or nano-encapsulated PCMs into a base fluid, is revolutionizing solar energy applications by enhancing thermal stability, storage capacity, and heat transfer efficiency. By utilizing the latent heat of PCMs, PCSs charge and discharge significant thermal energy, facilitating more efficient and dependable energy management. This capability is particularly valuable for addressing fluctuations in solar radiation, ensuring a stable heat supply even during periods of low solar intensity. The fluidic nature of PCSs allows seamless integration into conventional heat exchange systems, minimizing thermal losses and improving overall performance. With ongoing advancements in encapsulation techniques and material optimization, PCS technology is ready to play an essential role in next-generation solar thermal systems and other energy storage applications. Below, we provide a detailed analysis of how PCS optimizes solar energy systems [173], focusing on technical specifications, energy management, and performance enhancements (Fig. 12).

3.1.1. Applications of phase change slurry in heaters

Solar thermal heaters are vital for harnessing solar energy for direct heating applications like space and water heating. However, their performance is hindered by fluctuating solar intensity, leading to overheating during peak sunlight and insufficient heat during cloudy periods or at night [174]. PCS address these challenges by stabilizing temperature fluctuations and optimizing energy storage, ensuring consistent heating even in variable sunlight conditions.

Griffiths et al. [175] found that PCS effectively retained heat overnight, maintaining temperatures up to 50 °C until 6 a.m. However, prolonged use led to gradual decomposition, which reduced its overall effectiveness. Serale et al. [176] demonstrated that solar collectors operating at lower temperatures could still deliver sufficient energy, thereby enhancing efficiency under suboptimal conditions. Eames and Griffiths [177] showed that PCS, with its high latent heat storage (around 58–60 °C), significantly boosts energy capture, despite its lower

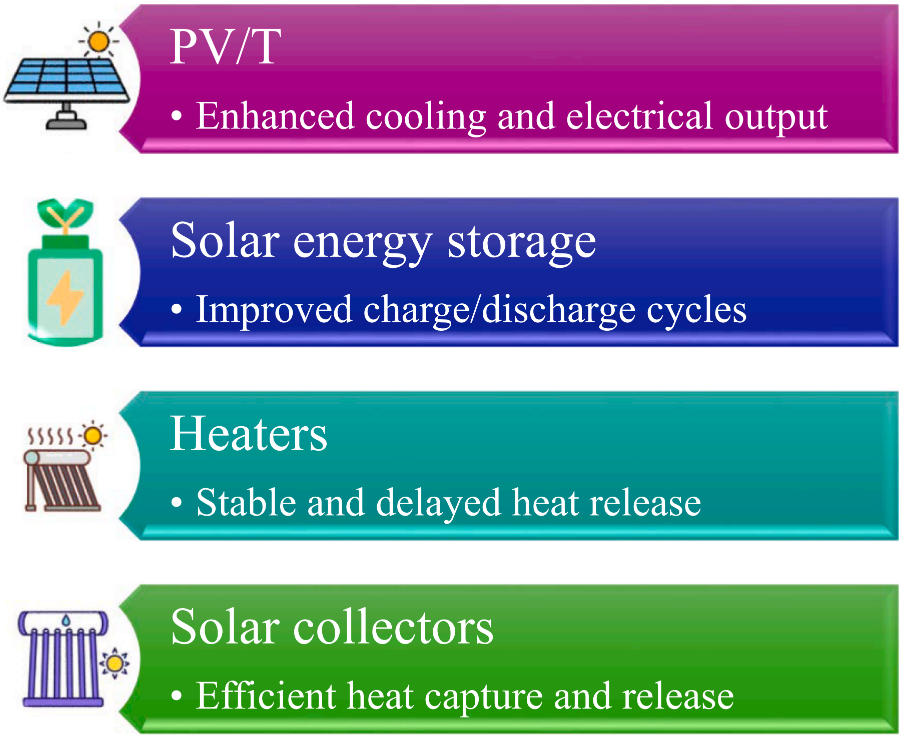


Fig. 12. Schematic representation of main application areas of PCSs in solar thermal systems.

specific heat capacity compared to water (Fig. 13).

Serale et al. [156] developed and tested a novel low-temperature solar thermal heating system that utilizes a microencapsulated phase change slurry (mPCS) as both the heat transfer and storage medium. The slurry consisted of n-eicosane as the PCM, encapsulated in microcapsules with diameters ranging from 17 to 20 µm, suspended in a 40 wt% glycol–water solution. The PCM exhibited a phase change temperature range of 36–38 °C and a latent heat of 195 kJ/kg. Thermal characterization displayed that the solidification specific enthalpy was 48 kJ/kg at 30 wt% PCM concentration and 62 kJ/kg at 40 wt%. The mPCS allowed the system to operate efficiently at low thermal levels, with an outlet temperature maintained near 40 °C through PID-controlled pumping. Compared to traditional water-based systems, the mPCS-enhanced system demonstrated a 5–9 % increase in seasonal collector efficiency, depending on boundary conditions. Cost analysis showed an initial additional cost of 2460 €, primarily due to the high cost of microencapsulated PCM, though this is expected to decrease with broader adoption. Overall, the study demonstrated the feasibility and performance advantages of using mPCS in solar thermal applications, particularly for low-temperature heating and thermal energy storage.

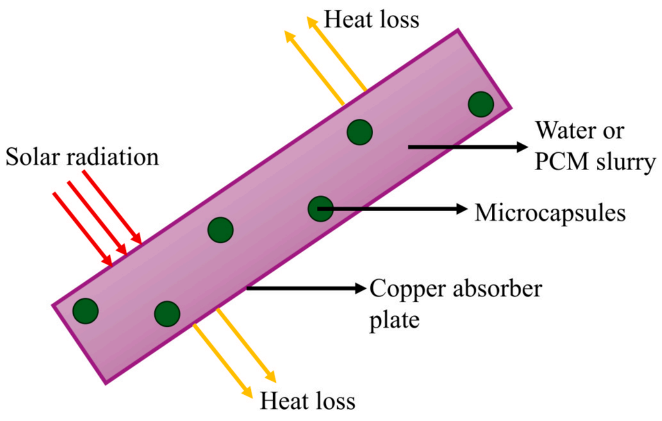


Fig. 13. The schematic representation of the heating system [177].

Key advancements in PCS for solar heaters include improved thermal energy storage capacity, better temperature regulation, and enhanced energy efficiency through the usage of latent heat. These benefits help stabilize system operation, diminish thermal stress, and minimize dependence on auxiliary heating. However, several limitations still prevent broader implementation. Long-term stability issues, such as phase separation, PCM leakage, and degradation during thermal cycling, can impact performance and reliability. Furthermore, the inherently low thermal conductivity of many PCMs poses a challenge to efficient heat transfer, necessitating the incorporation of advanced shell materials or conductive additives. Encapsulation techniques must also be refined to maintain structural integrity under repeated phase transitions.

Even though these benefits exist, several barriers remain for broader adoption. Long-term stability issues, including phase separation and degradation, can affect performance over time. Augmenting thermal conductivity whereas maintaining structural integrity is another curial part requiring further research. In addition, optimizing encapsulation methods to hinder leakage and provide durability remains a key concern. Scalable and cost-effective manufacturing processes are vital to facilitate commercial viability. Future work should prioritize enhancing encapsulation technologies, developing high-performance, green PCS materials, and conducting large-scale field trials to validate performance under real-world conditions. Tackling these challenges will be necessary to unlocking the PCSs' entire capabilities in solar thermal applications and ensuring its long-term success in renewable energy systems.

3.1.2. *Applications of phase change slurry in PV/T systems*

PV/T hybrid systems combine PV panels with thermal collectors to generate both heat and electricity at the same time. However, PV panel efficiency decreases as they heat up, and the excess heat is often wasted [178]. PCS offer a dual solution, enhancing both electrical and thermal outputs of PV/T systems [179].

Salem et al. [180] found that microencapsulated PCM (MPCM slurry improved heat transfer and reduced PV panel temperatures but required higher pumping power at increased concentrations. Fu et al. [181]

reported a 13.5 % boost in thermal efficiency and a 0.8 % increase in electrical efficiency with MPCM slurry compared to water-based systems. Jia et al. [182] identified optimal conditions (20 wt% slurry, 0.010 m channel height, 0.005 kg/s flow rate) but noted incomplete PCM melting at higher concentrations. Eisapour et al. [183] demonstrated that MPCM nano-slurry with wavy tube configurations increased exergy efficiency by 4.25 % and primary effectiveness by 6.06 % (Fig. 14).

These studies underscore the benefits of utilizing PCS in PV/T systems, such as enhanced thermal regulation, improved electrical efficiency, dual-mode energy harvesting, and extended system lifespan. PCS effectively absorbs excess heat through latent heat storage, preventing overheating of PV panels and allowing for simultaneous thermal and electrical energy generation. Despite these advantages, several challenges limit the widespread deployment of PCS in PV/T applications. Notably, higher slurry concentrations can increase viscosity, leading to high pumping power requirements and diminished system efficiency. To address this, future research should focus on optimizing slurry flow characteristics and exploring low-viscosity formulations. Additionally, incomplete PCM melting in low-irradiance or rapidly changing weather conditions can restrict energy storage potential, highlighting the need for advanced encapsulation techniques and improved thermal conductivity. Ensuring long-term material stability and developing scalable, cost-effective production processes will also be essential for real-world deployment. Ongoing innovations in nanomaterial integration, smart system control, and thermal performance monitoring may help overcome these barriers and accelerate PCS adoption in next-generation PV/T systems.

3.1.3. *Applications of phase change slurry in solar energy storage systems*

Solar energy storage systems are crucial for managing solar power intermittency, storing surplus energy during peak sunlight for use during low or no sunlight periods [184]. PCM-based thermal storage systems offer significant advantages over conventional methods, including superior thermal stability [185], higher energy density [186], and greater scalability [187]. Zhang et al. [188] found that higher PCM concentration and storage temperature increased energy storage capacity, though greater mass concentration and closure height delayed heat storage. Key findings include that Huang et al. [189] showed that heat exchanger size and placement significantly influenced the performance of slurry-based residential thermal storage systems. Ma et al. [190] developed a paraffin@SnO_2/CNTs composite with 42.94 % encapsulation efficiency, improved thermal stability, and 91.79 % solar absorption at 40 °C. Yuan et al. [191] demonstrated that paraffin@SiO_2/GO maintained paraffin-like phase change properties while enhancing photo thermal conversion, heat capacity, and thermal conductivity (Fig. 15). Additional studies are summarized in Table 5.

Key advantages of PCS include grid integration, temperature stability, long-duration storage, scalability, and high energy density. PCS offers compact, high-density storage through the latent heat of PCMs, enabling stable energy release over extended periods—critical for off-grid systems and CSP plants. Its phase change properties provide consistent thermal control, making it suitable for residential and industrial heating applications. The PCSs' modular nature ensures for easy integration into existing solar systems, whereas its ability to store surplus solar energy aids grid stability in areas with high solar penetration.

However, challenges remain in optimizing PCS for large-scale applications. Issues such as delayed heat storage at higher PCM concentrations can reduce the system's responsiveness and heat retention efficiency. Thermal degradation over time, caused by repeated phase transitions, can further diminish the overall performance and lifetime of PCS materials. Lastly, incomplete phase transitions at certain temperatures can result in efficiency losses, limiting the effectiveness of the system.

3.1.4. *Applications of phase change slurry in solar collectors*

Solar collectors, essential for converting solar radiation into usable heat, face challenges like heat transfer efficiency, temperature regulation, and thermal losses during peak solar intensity [196]. PCS addresses these issues by improving the thermal and optical properties of HTFs [197] and stabilizing collector temperatures [198], enhancing overall system performance [199].

Key findings include that Serale et al. [200] showed that increasing PCM fraction from 30 % to 40 % improved energy conversion by 4–6 %, with PCS enhancing solar utilization based on climate conditions. Karami et al. [201] found that CuO/Al_2O_3 nanofluids outperformed CuO-only systems, with CuO MPCM slurry boosting efficiency by 4.53 % and reducing heat losses by 5.84 %. Ran et al. [202] reported that MPCS-based flat-plate collectors achieved 71.1 % efficiency under optimal conditions, with efficiency rising with higher latent heat and mass concentration but decreasing with increased solar irradiation. Ma and Zhang [203] found that PCS-based volumetric collectors' efficiency correlated with slurry velocity and solar intensity, though high attenuation coefficients impacted performance. Zhu et al. [204] developed nano-enhanced PCMs with a SiO_2/graphene shell, increasing thermal conductivity by 132.9 % and photo-thermal conversion by 31–70 % in direct absorption solar collectors (Fig. 16). Additional studies are summarized in Table 6.

PCM-HTFs enhance solar collector performance by improving heat transfer, regulating temperature, increasing durability, and enabling

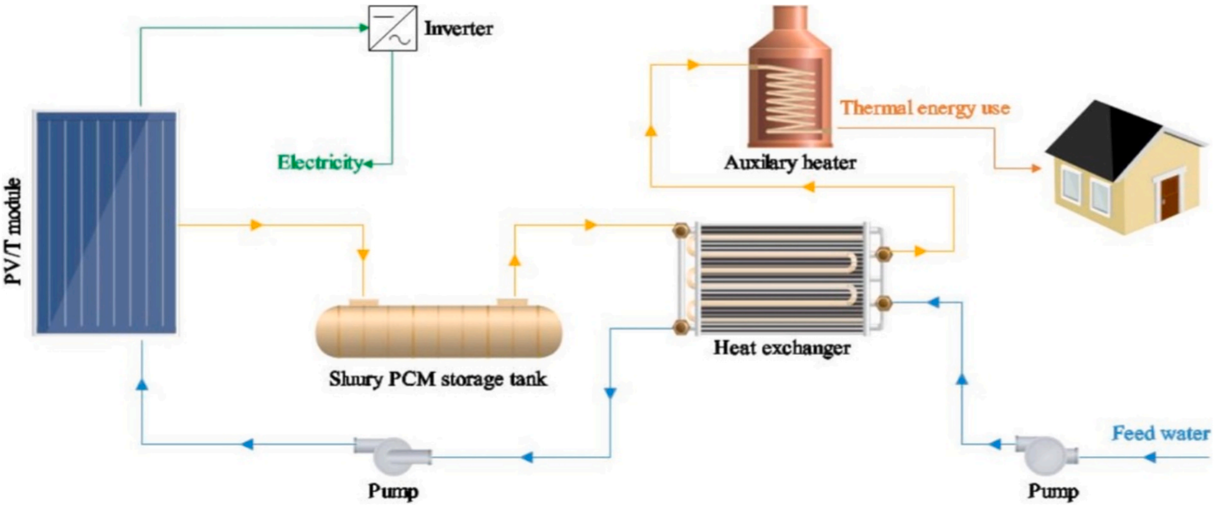
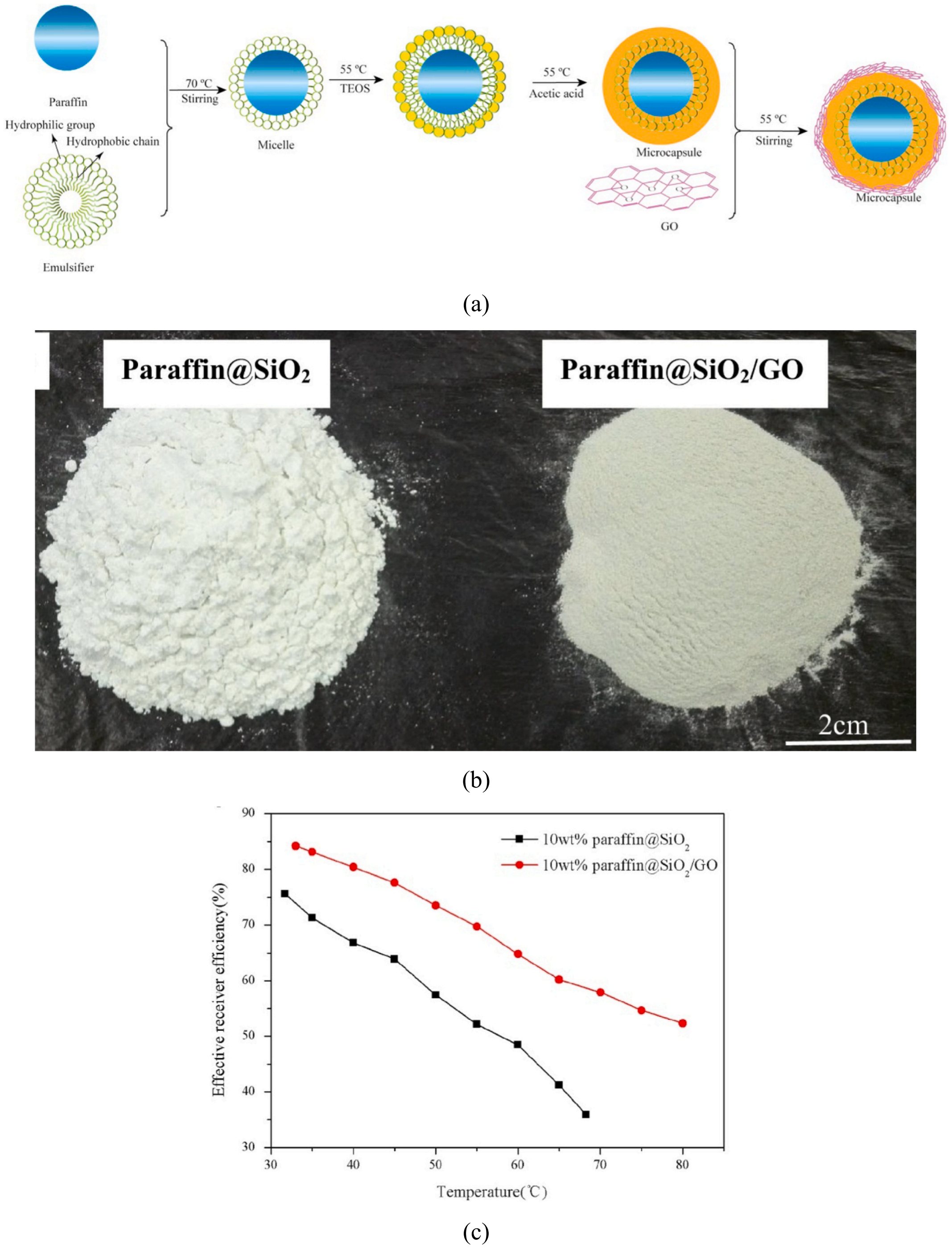


Fig. 14. Schematic of the system operation for building applications [183].



(a)

(b)

(c)

Fig. 15. (a) A scheme for preparing paraffin@SiO2/GO composite, (b) SEM images of paraffin@SiO_2 and paraffin@SiO_2/GO, and (c) effective receiver efficiency of direct absorption solar collector based on paraffin@SiO_2 and paraffin@SiO_2/GO-dispersed slurries (f) [191].

efficient storage integration. Encapsulated PCMs boost thermal conductivity, ensuring effective energy capture and transfer while preventing overheating. This is achieved by storing and gradually releasing excess thermal energy, providing stable temperature control throughout the day [210]. Additionally, PCS helps reduce thermal cycling stress, which extends the lifespan of collector components, lowers maintenance costs, and improves overall system reliability. By allowing direct heat storage within the fluid, PCS eliminates the need for external storage devices, facilitating continuous operation even in low sunlight conditions, such as early mornings, evenings, or cloudy days.

Furthermore, the integration of PCM-HTFs in solar collectors offers significant improvements in energy efficiency, as they allow for better utilization of available solar radiation and enhance the system's ability to deliver heat during periods of high demand. The ability to store excess heat in the fluid also makes the system more responsive and adaptable to varying environmental conditions. Despite these significant advantages, challenges remain in optimizing PCM-HTFs for large-scale applications. Issues such as attenuation effects, where the heat transfer performance degrades with time, phase separation of the PCM, and long-term stability under high thermal loads need to be addressed. Additionally, ensuring that the PCM remains stable throughout many charge–discharge cycles without significant degradation is essential for long-term operational efficiency.

Despite promising performance at the laboratory scale, the PCM-

Table 5
PCS in solar energy storage systems.

Study	Key findings	References
Stearic Acid@MWCNTs composite PCM	47 % encapsulation; melting point at 59.3 °C; latent heat ~ 92 J/g; enhanced water slurry temperature range.	Chen et al. [192]
Paraffin@Cu-Cu2O/CNTs microencapsulated PCM	Higher decomposition temp (+97 °C); improved light-to-heat conversion and better heat storage in water.	Xu et al. [193]
Microencapsulated PCM in ethylene glycol aqueous	Latent heat storage increased with PCM concentration; best performance with me-SAL slurry.	Boldoo et al. [194]
Nano-encapsulated PCM in metal shells for light-heat conversion	Storage capacity boosted by 68–92 %; thermal capability increased up to 554 % with higher paraffin content.	Kazaz et al. [195]

HTFs' scalability for industrial applications remains a significant challenge. Key barriers include the high costs associated with large-scale encapsulation processes, difficulties in maintaining uniform particle size and encapsulation quality during mass production and ensuring stable dispersion of micro- and nano-encapsulated PCMs in carrier fluids at industrial volumes. Moreover, increased slurry viscosity and potential sedimentation raises pumping power requirements and operational complexity. Long-term durability and performance under continuous industrial operation also require further validation. Addressing these challenges will necessitate the development of cost-effective, scalable manufacturing methods, enhanced material formulations for dispersion stability, and extensive field testing to confirm reliability and efficiency in real-world conditions. Future research should focus on these aspects to facilitate the PCM-HTFs' broader commercial adoption in large-scale thermal energy systems.

3.1.5. *Techno-economic and environmental considerations of phase change slurries in solar systems*

While PCM-HTFs provide significant promises for enhancing the performance of solar energy systems, their practical deployment is strongly influenced by techno-economic and environmental factors. From a cost perspective, the price of PCMs varies considerably depending on their chemical nature and encapsulation method. Organic PCMs (e.g., paraffins) are relatively low-cost and abundant, typically ranging from ~$2–5/kg [211], but suffer from low thermal conductivity and flammability concerns. Inorganic PCMs (e.g., salt hydrates) offer higher latent heat capacities and better cost-performance ratios (~ $0.2–5/kg) [211], but issues such as corrosion and phase segregation raise maintenance costs. Encapsulation introduces additional cost layers, with chemical methods such as interfacial polymerization often being more expensive due to reagent cost and process control requirements. Estimates suggest that the total cost of encapsulated PCM slurries depends on the shell material and technique used. Scalability remains a challenge for some high-performance encapsulation methods, which may not be feasible for industrial-scale production without process innovation or automation.

Commercial readiness of PCS technologies is still in the early to mid-development stages, with most applications confined to laboratory or pilot-scale demonstrations. While some commercial products based on microencapsulated PCMs exist, large-scale adoption is limited by the lack of standardization, high material costs, and challenges related to long-term stability and integration into existing solar thermal infrastructure. For widespread industrial uptake, scalable fabrication methods such as spray drying, solvent-free encapsulation, and continuous-flow microfluidic [212] methods must be further optimized to diminish costs and enhance efficiency.

From an environmental and lifecycle perspective, several concerns must be addressed to ensure sustainable application of PCM-HTFs. Organic PCMs derived from petroleum sources may present biodegradability and toxicity challenges if leaked into the environment [213]. Inorganic PCMs such as salt hydrates can contribute to corrosion or water contamination if not properly contained [214]. Shell materials used may not be biodegradable, raising concerns over long-term waste accumulation. Therefore, recent research is shifting toward bio-based, recyclable, and environmentally benign encapsulation materials, such as starch-based shells, polylactic acid (PLA), or silica derivatives. Additionally, the life-cycle environmental impact of encapsulated PCS should account for the embodied energy and emissions associated with their synthesis, use, and disposal. Integration of green chemistry principles and life-cycle assessment (LCA) frameworks will be crucial to minimize environmental footprints and guide material selection for future PCS development.

3.2. *Current challenges*

The integration of micro-/nano-encapsulated PCMs into HTFs for solar energy applications offers significant potential but faces several challenges. One of the primary limitations is the inherently low thermal conductivity of most PCMs, which restricts the rate of heat transfer. While encapsulation increases surface area, it doesn't fully resolve this issue. Adding high-conductivity fillers like metal nanoparticles or graphite can enhance thermal performance, but uniform dispersion, stability over time, and cost remain concerns. Another important challenge lies in the durability of the encapsulation shells. These shells must endure repeated thermal cycling and mechanical stress without rupturing, degrading or leaking. Polymer-based materials often lack the thermal stability needed for high-temperature solar systems, particularly in CSP systems, where material integrity is essential over extended operational lifetimes.

The high manufacturing costs of current encapsulation methos also pose a barrier to large-scale implementation. Encapsulation processes like solvent evaporation and spray drying are expensive and complex, making large-scale production challenging. Consistent quality and cost-effective techniques are needed for widespread adoption. Compatibility with existing solar thermal system components presents additional challenges. PCM-HTFs must avoid causing corrosion, fouling, or adverse reactions with system components like pipes and heat exchangers. Moreover, viscosity changes during phase transitions can also impact fluid flow and pumping requirements.

Supercooling is another technical issue that can impair the reliability of thermal energy storage. In this phenomenon, PCMs remain in a liquid state even below their freezing point, thereby delaying or preventing the solidification process needed for effective energy release. Effective encapsulation must promote controlled nucleation to ensure consistent and reliable phase transitions under operational conditions. High-temperature performance remains a significant concern, particularly for applications in CSP plants. Many PCMs are prone to thermal degradation, phase separation, and changes in physical or thermal properties at elevated temperatures, which can compromise the long-term performance and safety of the system.

Furthermore, solar thermal systems demand dynamic response capabilities from PCM-HTFs. These materials must be able to adapt to rapidly changing solar radiation and fluctuating thermal loads, efficiently storing and releasing heat in response to varying energy demands throughout the day and across seasons. Environmental and safety considerations also play a vital role in material selection and system design. Some PCMs and encapsulation materials are non-biodegradable or potentially toxic, raising environmental and human health risks. Developing eco-friendly, non-toxic, and recyclable materials is crucial for sustainable deployment.

Finally, the absence of standardized testing protocols makes it challenging to assess and compare the performance of different PCM formulations. There is a critical need for globally recognized standards to evaluate encapsulation integrity, thermal properties, cyclic stability,

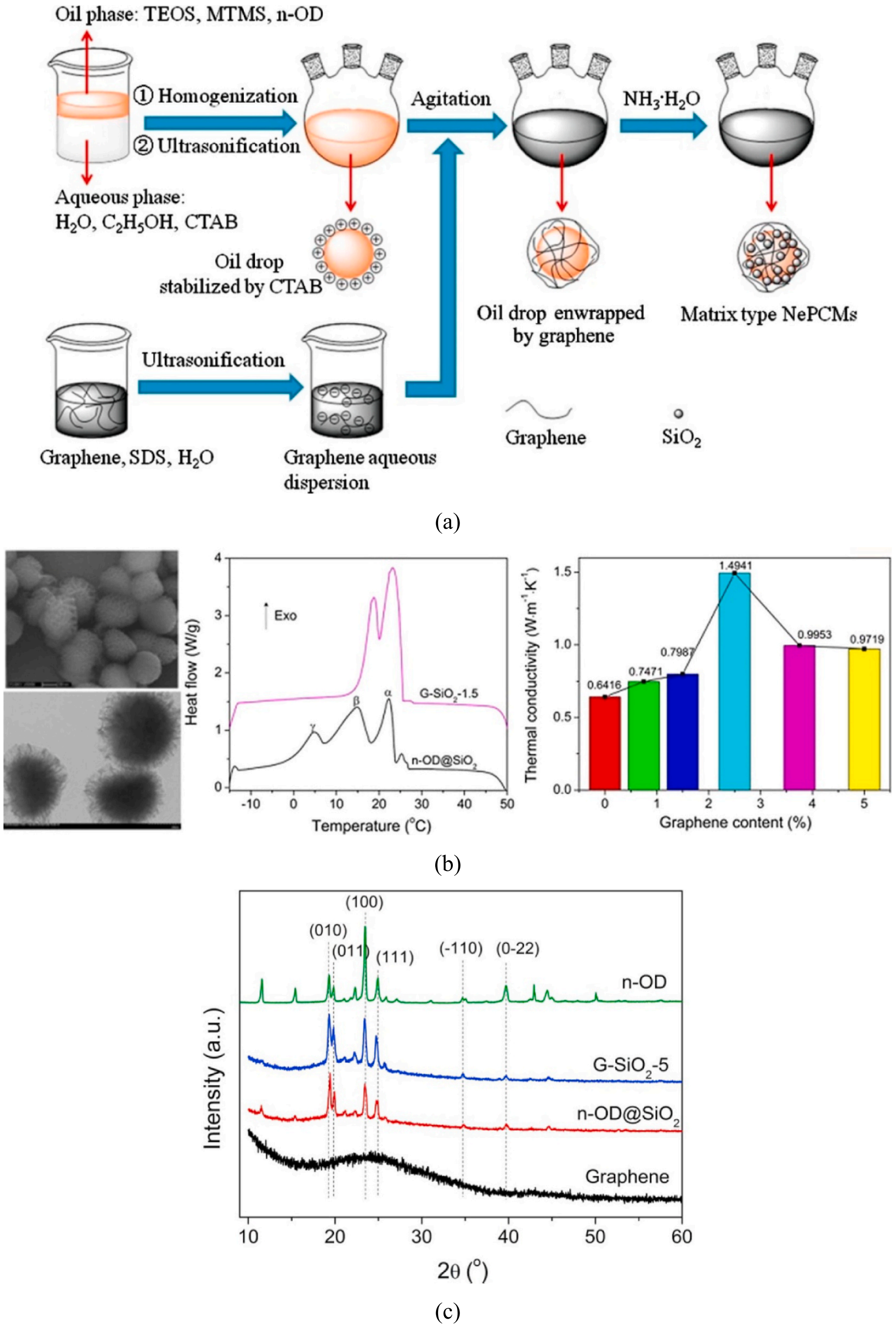


Fig. 16. (a) Process for preparation of the NePCMs with SiO_2/graphene composite shell, (b) morphology, heat flow and high thermal conductivity, and (c) XRD curves of n-OD, graphene, n-OD@SiO_2, and G-SiO_2-5 [204].

and long-term durability to ensure the reliability and commercial readiness of PCM-HTFs. Mitigating these challenges is important for the practical implementation and optimization of PCM-HTFs in solar energy systems.

3.3. Recommendation for future works

Future advancements in PCM-HTFs should prioritize the innovation of high-performance phase change materials characterized by superior thermal stability, elevated phase transition temperatures, and enhanced

Table 6
PCS in solar collectors.

Study	Key findings	References
Thermal capacity of in flat liquid solar collectors	Slurry improved thermal efficiency by 4–6 %; exhibited lower outlet temperature than water under same conditions.	Bohdal et al. [205]
Heat transfer enhancement using slurry	Viscosity remained similar to water below 20 % PCM; increased significantly above 45–50 % PCM content.	Serale at al. [206]
Thermal characteristics in volumetric solar collectors	Phase change boosted local Nusselt number; high Reynolds number and top-placed absorbers enhanced heat gain.	Siddiqui and Yilbas [207]
MPCM-MWCNT slurry for light-to-heat conversion	Provided higher terminal temperatures and better solar-thermal conversion than standard nanofluids.	Wang et al. [208]
Phase change slurry in trombe wall for thermal comfort	DPTW improved indoor heating duration by 167 % and reduced winter heat load by 39 % over conventional systems.	Xu et al. [209]

thermal conductivity, particularly for elevated-temperature solar thermal and industrial applications, such as CSP. A promising avenue for exploration involves the systematic design and optimization of eutectic mixtures—such as sodium nitrate-potassium nitrate salts or organic-organic systems—and low-melting-point metal alloys, including gallium-indium or tin-zinc. These materials can be methodically engineered to broaden the operational temperature range while preserving a high latent heat storage capacity. Empirical investigations utilizing differential scanning calorimetry, thermogravimetric analysis, and accelerated thermal cycling methodologies can substantiate their performance and long-term stability.

To mitigate the intrinsic low thermal conductivity of PCMs, forthcoming research endeavours should explore the integration of nanomaterials, including graphene nanoplatelets, silver or copper nanoparticles, and carbon nanotubes. These additives possess the potential to establish conductive percolation networks that markedly enhance thermal response. Comprehensive analyses employing scanning electron microscopy, infrared thermography, and transient hot-wire techniques can clarify the mechanisms underlying heat transfer enhancement and contribute to the optimization of loading ratios. Additionally, it is crucial to evaluate the implications of nanomaterial incorporation on slurry viscosity and pumpability, particularly in flow-based systems, which should be thoroughly examined through rheological assessments and flow loop experiments.

In the realm of encapsulation, the forthcoming generation of PCM-HTFs will derive significant advantages from the utilization of intelligent and multifunctional shell materials. The advancement of stimuli-responsive encapsulation systems—such as those predicated on thermochromic or shape-memory polymers—can facilitate dynamic regulation of phase transitions and mitigate supercooling phenomena. The experimental assessment of such systems should encompass real-time monitoring of thermal responses and in situ visualization of phase changes. Moreover, multi-layer encapsulation strategies incorporating self-healing polymers or high-strength interlayers can enhance mechanical resilience and durability under thermal cycling. These materials can be fabricated through techniques such as coaxial electrospinning or layer-by-layer assembly and evaluated through burst pressure tests and assessments of long-term fluidic stability.

From a manufacturing perspective, future investigations should delve into environmentally sustainable, scalable, and economically viable encapsulation methodologies. Solvent-free production techniques, such as reactive extrusion and UV-curing polymerization, present feasible pathways toward more environmentally responsible manufacturing. Microfluidic encapsulation approaches enable precise control over capsule dimensions and configurations, and their scalability can be demonstrated through the use of continuous flow microreactors. Furthermore, additive manufacturing methods, including 3D printing of PCM-infused components, could facilitate the production of customized heat exchanger modules tailored for solar or industrial applications. The performance of such printed modules can be rigorously evaluated under simulated solar flux conditions using solar simulators and thermal load testing protocols.

From a systems integration standpoint, the coupling of PCM-HTFs with hybrid thermal management systems that incorporate solar, geothermal, or wind energy can substantially enhance operational reliability. The integration of thermoelectric generators and battery storage systems can further enable effective thermal-to-electrical energy conversion. Experimental configurations that amalgamate solar collectors, PCM-HTF storage tanks, and thermoelectric generator modules can be employed to monitor heat flow, temperature differentials, and electrical output across various load conditions to comprehensively assess overall efficiency and reliability.

In order to enhance control mechanisms and operational intelligence, the incorporation of advanced sensor technologies into PCM storage systems facilitates real-time surveillance of phase states and temperature distributions. This collected data can subsequently be utilized to inform predictive models and machine learning algorithms, which are specifically designed to dynamically optimize system performance, orchestrate charging and discharging cycles, and identify anomalies. These models ought to be trained on empirical data derived from thermal cycling, heat recovery efficacy, and environmental conditions to guarantee adaptability and precision.

Sustainability must persist as a fundamental priority in forthcoming research endeavours. Investigations should concentrate on the application of bio-based and biodegradable materials—such as polylactic acid, starch, or cellulose-based encapsulating shells—and the utilization of eco-friendly solvents or solvent-free synthesis techniques should be prioritized to mitigate environmental repercussions. Comprehensive LCA and techno-economic analysis must be performed to scrutinize the feasibility and environmental impact of the proposed materials and manufacturing methodologies. Furthermore, additional environmental evaluations—including assessments of biodegradability, leaching, and toxicity—will bolster regulatory compliance and ensure long-term ecological safety.

Ultimately, large-scale validation of PCM-HTFs under authentic environmental conditions is of paramount importance. Field trials involving rooftop solar thermal systems, industrial waste heat recovery units, or solar-assisted desalination projects across diverse climatic regions should be executed to assess long-term performance, degradation behaviour, and integration challenges. These trials should be augmented by international collaboration to formulate standardized testing protocols, safety regulations, and environmental benchmarks that will expedite the commercialization and widespread implementation of PCM-HTFs in sustainable energy infrastructures.

Last but not least, while laboratory-scale research on PCM-HTFs has demonstrated promising thermal performance and material stability, there remains a notable gap in real-world validation. Future efforts should prioritize the design and execution of pilot-scale and full-scale demonstration projects in diverse climatic conditions to assess long-term reliability, system integration, and performance under dynamic solar loading. The limited number of existing case studies underscores the urgent need for expanded field testing to bridge the gap between experimental findings and practical deployment. Collaboration between academic institutions, industry stakeholders, and energy utilities will be vital for generating robust datasets, optimizing system designs, and accelerating the commercialization of PCM-HTFs in solar energy systems.

4. Conclusions

Micro- and nano-encapsulated PCM-based heat transfer fluids (PCM-HTFs) signify a state-of-the-art development in solar energy applications, providing a synergistic blend of improved thermal energy storage and heat transfer. These innovative materials address critical challenges in solar thermal systems by mitigating temperature fluctuations, optimizing heat utilization, and improving energy efficiency. As global demand for renewable energy solutions grows, PCM-HTFs have the potential to transform solar thermal energy storage, making it more versatile, reliable, and effective under diverse operational conditions.

This review comprehensively explored different types of PCMs, various encapsulation techniques, and novel PCM-HTFs designed for solar energy systems. The encapsulation of PCMs into micro- and nano-sized shells enhances their thermal stability, prevents leakage, and improves their integration into heat transfer fluids. By maintaining phase change capabilities while offering better dispersion and compatibility with conventional heat transfer fluids, these materials have demonstrated significant potential for boosting the overall performance of solar thermal technologies. Furthermore, their adaptability in applications such as CSP, solar water heating, and hybrid energy systems underscores their relevance in modern energy solutions.

Despite their advantages, several barriers hinder the broad implementation of PCM-HTFs. Difficulties such as low thermal conductivity, phase separation, scalability, long-term stability remain key areas of concern. Enhancing the PCMs' thermal conductivity through composite materials, improving encapsulation shell durability, and developing cost-effective large-scale manufacturing techniques are crucial to overcoming these challenges. Additionally, long-term performance and environmental sustainability must be considered, particularly in selecting biodegradable and non-toxic encapsulation materials to minimize ecological impact.

Future research should focus on high-performance PCMs with superior thermal properties, the development of smart and adaptive encapsulation materials, and scalable manufacturing processes that enable mass production without compromising quality. The integration of PCM-HTFs into hybrid renewable energy systems, such as thermo-photovoltaic systems and solar-thermal-electric, can further enhance energy efficiency. Additionally, interdisciplinary collaboration among material scientists, engineers, and industry stakeholders, along with large-scale field trials, will be vital for optimizing real-world applications. Establishing international standards and regulatory frameworks will also accelerate commercialization and ensure consistent performance across various applications.

In conclusion, PCM-HTFs hold immense promise for advancing solar energy efficiency, thermal storage capacity, and system sustainability. By addressing the existing challenges and fostering innovation, these materials can drive the global transition toward cleaner and more sustainable energy solutions, making solar thermal technologies more viable and impactful in the long run.

CRediT authorship contribution statement

Oguzhan Kazaz: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Nader Karimi:** Writing – review & editing, Supervision. **Manosh C. Paul:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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