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Innovations in phase change materials for diverse industrial applications: A comprehensive review

Vennapusa Jagadeeswara Reddy [a], Mohd Fairusham Ghazali [a,b], Sudhakar Kumarasamy [b,c,d,*]

[a] Centre for Research in Advanced Fluid & Processes, Universiti Malaysia Pahang Al Sultan Abdullah, 26300 Gambang, Pahang, Malaysia
[b] Faculty of Mechanical and Automotive Engineering Technology, Universiti Malaysia Pahang Al Sultan Abdullah, 26600 Pekan, Pahang, Malaysia
[c] Centre for Automotive Engineering, Universiti Malaysia Pahang Al Sultan Abdullah, Pekan 26600, Pahang, Malaysia
[d] Energy Centre, Maulana Azad National Institute of Technology, Bhopal 462003, M.P, India

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ABSTRACT

The need for effective and sustainable thermal management systems is expanding across a variety of industries, and phase change materials (PCMs) have become a flexible alternative to meet this demand. The ability of phase change materials to store significant amounts of heat during their phase transition over a constrained temperature range make them attractive candidates for temperature regulation or energy storage applications in several industrial sectors. This review paper examines recent developments in PCM applications and their significant effects on a range of industries, including building and construction, solar energy storage, electronics, automobiles, pharma and health care, waste heat recovery, electricity generation, water treatment, food and beverages, and textiles. The article starts off by giving a basic overview of PCMs and explaining their distinctive thermal properties, classification, and operating principles. It then delves into the in-depth study, covering the recent advancements of PCM applications. This extensive assessment covers both prospective directions for further study and development as well as the crucial elements influencing the practical application of PCMs. Overall, this article provides a thorough summary of the developments in PCM applications across a range of industries, emphasizing their enormous potential to improve energy efficiency, lower carbon emissions, and promote sustainable development. It is a useful resource for scientists, engineers, and decision-makers working in the domains of thermal engineering, energy management, and materials science. It encourages greater PCM innovation and application for a more sustainable and efficient world.

1. Introduction

Global energy consumption has significantly increased in recent decades as a result of population growth, urbanization, industry, and technological improvements [1]. Energy demand, which is mostly met by fossil fuels, has increased, posing numerous economic, social, and environmental problems [2]. For many years, fossil fuels have been the main source of energy in the globe, but their extraction, transportation, and use have had negative effects on the environment. Massive volumes of greenhouse gases, such as carbon dioxide and methane, are released into the atmosphere when fossil fuels are burned, which greatly contributes to global warming and climate change. Rising sea levels, severe weather, ice cap melting, and ecosystem upheaval are some of the results. The overuse of fossil fuels like coal, oil, and natural gas has exacerbated climate change, the destruction of the environment, and geopolitical tensions. In contrast, renewable energy sources like biomass, solar, wind, hydro, and geothermal energy provide a hopeful response to these issues. In order to tackle climate change, improve energy security, and safeguard the environment for future generations, we must switch to clean and sustainable energy sources [3]. Adopting these alternatives is both morally required and a chance for global advancement as renewable energy technologies develop and become more commercially viable. The main issue with employing renewable energy sources is that they provide energy intermittently and in unexpected amounts depending on the weather [4].

Phase change materials (PCMs) can be extremely useful for storing renewable energy, particularly for coping with the unpredictable and fluctuating nature of renewable energy sources like sun and wind. The ability of PCMs to store significant volumes of latent heat has various benefits for storing renewable energy by utilizing them as effective

* Corresponding author at: Centre for Automotive Engineering, Universiti Malaysia Pahang Al Sultan Abdullah, 26000 Pekan, Pahang, Malaysia.
E-mail address: sudhakar@ump.edu.my (S. Kumarasamy).

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thermal energy storage devices [5]. The PCM can be heated to cause it to change phase, usually from solid to liquid, when extra energy is produced from renewable sources, such as during sunny or windy days. Until it is required, the energy is stored in the substance [6]. The stored energy in the PCM is released as it transforms back to its solid state, providing a consistent and dependable energy source when the need for energy exceeds the supply from renewable sources (for example, at night or on overcast days). Renewable energy systems can better match energy supply and demand by utilizing PCMs. As a result, less energy is wasted when it is generated but not immediately used, which will increase the overall efficiency of renewable energy sources. By serving as a buffer between the fluctuating renewable energy supply and the steady energy consumption, PCMs can aid in the stabilization of the electrical grid. This could lessen the requirement for fossil fuel backup power generation and increase grid stability. PCMs can help reduce greenhouse gas emissions and the dependency on fossil fuels for emergency power by encouraging the effective use of renewable energy. PCMs are available in a variety of kinds and phase change temperatures, making them appropriate for a wide range of applications, from small-scale grid systems to household energy storage. The research focus over the phase change materials is growing continuously in the last decade which could be seen from the Fig. 1. The number of publications per year in last ten years is increasing gradually reaching about 10,479 publications published on the phase change material topic in one-year 2022 from 4215 publications in 2012.

Novelty statement of the work

The recent review studies published on the applications of PCMs in literature and the topics covered in those articles are presented in Table 1. Based on the recently published review articles on the applications of PCMs, it is evident that most of the review articles focused on demonstrating one specific application or a few prominent application areas like buildings, textiles, solar energy storage etc. Very few articles were published discussing the diverse application fields of PCMs. So, a clear literature gap exists in presenting a study that could illuminate the significant application areas of the PCM.

This review article offers a unique perspective on Phase Change Materials (PCMs) by surveying recent research across ten distinct industrial sectors. Unlike previous studies focusing on a single application area, this work presents a comprehensive overview of PCMs' potential in various fields. By shedding light on the diverse roles of PCMs, this review aims to enlighten young researchers in the thermal energy storage applications using PCMs. Additionally, we have prioritized recent publications within the past 3–5 years to ensure the information is most up-to-date and relevant for broader applications.

2. Overview of phase change materials

The term "phase change material" (PCM) refers to a class of substances that can store and release enormous amounts of energy in the form of latent heat by switching phases, often from solid to liquid or vice versa. They are extensively utilized in thermal energy storage applications, mainly for heating and cooling systems. PCMs can be applied in temperature stabilization and latent heat thermal energy storage systems for power generation. Heat is absorbed by PCMs when they melt and released when they solidify. As a result, they can serve as a thermal buffer, minimizing temperature changes and the energy required for the heating and cooling systems. This can result in energy savings and a more comfortable indoor environment. The performance of a PCM-based thermal energy storage system is significantly influenced by the PCM's characteristics, including thermal conductivity, melting point, operating temperature range, energy storage capacity and heat of fusion.

2.1. Types of phase change materials

Classifying phase change materials primarily relies on their phase transition behavior, resulting in two main varieties. The materials that experience a change in phase from one solid state to another solid state can be classified as solid–solid phase change materials (PCMs). In contrast, materials that endure a transition from a solid to a liquid state are referred to as solid–liquid PCMs [28,29]. Solid-liquid phase change materials (PCMs) can store significant quantities of thermal energy compared to their counterparts. As a result, they have been extensively investigated for their potential applications across diverse disciplines. There are multiple classifications for solid–liquid phase change materials (PCMs), mainly categorized into three overarching groups based on their composition: organic, inorganic, and eutectic PCMs [30,3132]. Organic phase change materials (PCMs) encompass plant oils, vegetable fats, paraffins, and compounds derived from fatty acids [33,34]. On the other hand, inorganic PCMs consist of metal salts, salt hydrates, and metals. Eutectic phase change materials (PCMs) exhibit distinct characteristics and are created through the combination of two or more individual PCMs [35,36,37]. The phase change materials (PCMs) employed in these eutectic mixtures may consist solely of organic PCMs, exclusively of inorganic PCMs, or a combination of organic and

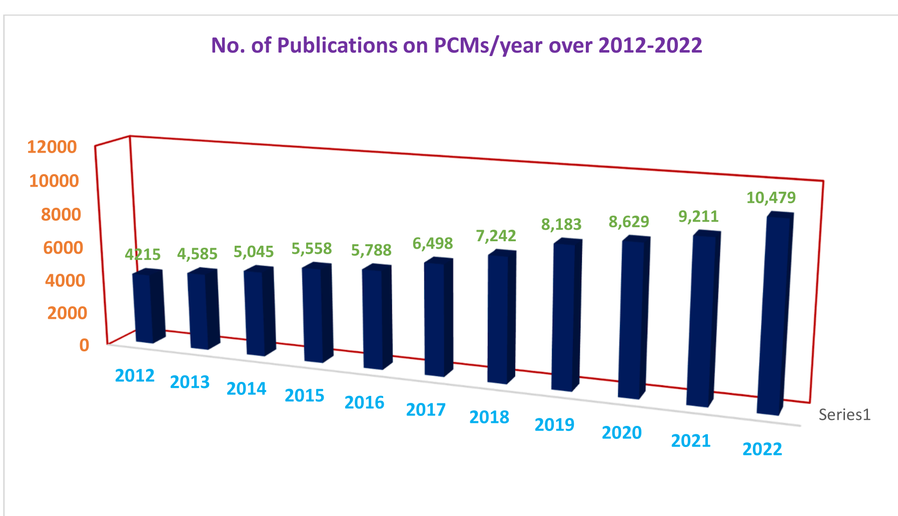

Fig. 1. Number of research articles published on phase change materials from 2012 to 2022
Source: scopus.com, search phrase: phase AND change AND materials [7].

Table 1
Summary of Recent Articles on Industrial Applications of Phase Change Materials (PCMs).

Authors	Year of publication	Focus areas
Togun et al. [8]	2024	Critically reviewed PCM-based heat exchangers and discussed different hybrid techniques for enhancement of performance.
Jayathunga et al. [9]	2024	Discussed about exploiting the latent heat storage ability of PCMs in concentrated solar power thermal applications
Yang et al. [10]	2024	Presented the discussion on advances in PCMs, thermal properties enhancement techniques and applications for textiles, buildings, battery thermal management and catalysis applications
Li et al. [11]	2024	Reviewed the recent prospects of various forms of stable composite PCM applications for high-temperature cooling of Li-ion batteries
Chen et al. [12]	2024	Discussed the current status of integration of PCMs in cold chain refrigerated trucks for energy conservation and emission reduction
Zhang et al. [13]	2024	Reviewed the encapsulation and functionalization methods for PCMs and their applications in the medical field like medical textiles, medical equipment, drug delivery and cold storage and transportation
Khan et al. [14]	2024	Collected the literature and reviewed the recent progress on PCM applications for thermal management applications in spacecraft avionics by a European agency, NASA and Hexafly international mission etc.
Xu et al. [15]	2024	Discussed the recent progress on the heat storage technology based on PCMs for solar heat pump applications
GaneshKumar et al. [16]	2024	Presented the state-of-the-art review on PCM application for the efficient thermal management of Li-ion battery systems
Alavy et al.[17]	2024	Reviewed the usefulness of PCMs and their characteristics on the performance of geothermal and foundation-based energy systems
Reddy et al. [18]	2024	Discussed and reviewed the studies on the application of PCMs to various building components like windows, cement, walls, roofs, paints, bricks and floor
Wang et al. [19]	2023	Presented the literature compilation on the recent development of the application PCM for designing cool clothing
Ram et al. [20]	2023	Discussed the application of PCMs into solar energy-based thermal energy storage systems, reviewing the effect of thermophysical properties of PCMs on the performance of solar thermal collectors
Zare et al. [21]	2023	Comprehensively reviewed the applications of PCMs in life science applications such as drug delivery, human body, sensing, barcoding, food and AI applications.
Ge Wang et al. [22]	2023	Analyzed recent research on the diverse applications of Phase Change Materials (PCMs) across various fields, including energy conversion, medical textiles, mechanical engineering, catalytic processes, and multifunctional fabrics.
Hassan et al.[23]	2022	Discussed the advancements in the application of PCMs into the buildings and presented the state-of-the-art review
Ismail et al. [24]	2022	Reviewed Phase Change Materials (PCMs) and their diverse applications across various industries, including textiles, photovoltaic (PV) cooling, food preservation, automotive temperature regulation, battery performance enhancement, and asphalt pavement stabilization.
Bao et al. [25]	2022	Discussed the application of PCMs for designing intelligent drug delivery systems for cancer treatment
Diaconu et al.[26]	2022	Reviewed the literature on PCM-based application systems and their designs for various fields
Faraji et al. [27]	2021	Presented the review of various emerging configurations of PCMs for designing effective heat sinks
This work	2024	Covered most of the application fields of PCM in various industries (13 different industries) Discussed in detail about the studies that reported various applications of PCM

inorganic PCMs. The up-to-date classification of PCMs based on their phase change behavior and materials composition is shown in Fig. 2 [38,39].

2.2. Encapsulation of phase change materials

Encapsulation is a method employed to confine and safeguard phase change materials (PCMs) within a shell or, casing or enclosure, enabling their incorporation into diverse applications while avoiding direct exposure to the surrounding environment and the leakage of PCM during their phase transition from solid to liquid. Encapsulation can be carried out by casing PCM inside a non-porous shell(capsules) or by impregnation of liquid PCMs into porous particles called support matrices(composites) [40]. The size of the container also plays a vital role in improving the thermal performance of the PCM. Based on the size of the container, encapsulation is categorized into three types. They are macro, micro and nanoencapsulation, where the diameter of the shell falls in the size ranges of macro (>1000 μm) [41], micro (>1000 nm) and nano (<1 μm), respectively.

PCMs can be encapsulated inside organic or inorganic containers to form PCM capsules through various chemical, physical and physio-chemical encapsulation methods. Chemical methods of encapsulation are mainly used to create organic polymeric shells like melamine formaldehyde [42], PMMA [43] etc., through Insitu, mini emulsion, suspension, emulsion and interfacial polymerization methods [44,45]. In physiochemical encapsulation methods, inorganic shells primarily result from the sol–gel method, while biobased polymer shells are typically formed using the coacervation method. Although physical encapsulation methods for PCM encapsulation are not widely adopted, some techniques, such as solvent evaporation, spray drying, ionic gelation, and microfluidic encapsulation, have gained attention. [46,47]. Different encapsulation technologies offer unique advantages in terms of thermal performance, durability, and suitability for specific applications. The detailed classification of various encapsulation methodologies of phase change materials is presented in Fig. 3.

2.3. Nano-enhanced phase change materials

Nano-enhanced phase change materials (NEPCMs) are a type of PCM modified at the nanoscale to improve their thermal properties. These materials are made by incorporating nanoparticles, such as metal oxides or carbon nanotubes, into the PCM matrix. By doing so, the thermal conductivity of the PCM can be significantly increased, leading to faster heat transfer and a more efficient thermal energy storage system. Additionally, the addition of nanoparticles can also increase the stability and durability of the PCM. Some examples of NEPCMs include paraffin waxes with nanoparticles of carbon nanotubes or metal oxides [48,49,50], and PCMs with a high thermal conductivity due to their nanocomposite structure. These NEPCMs have been used in various

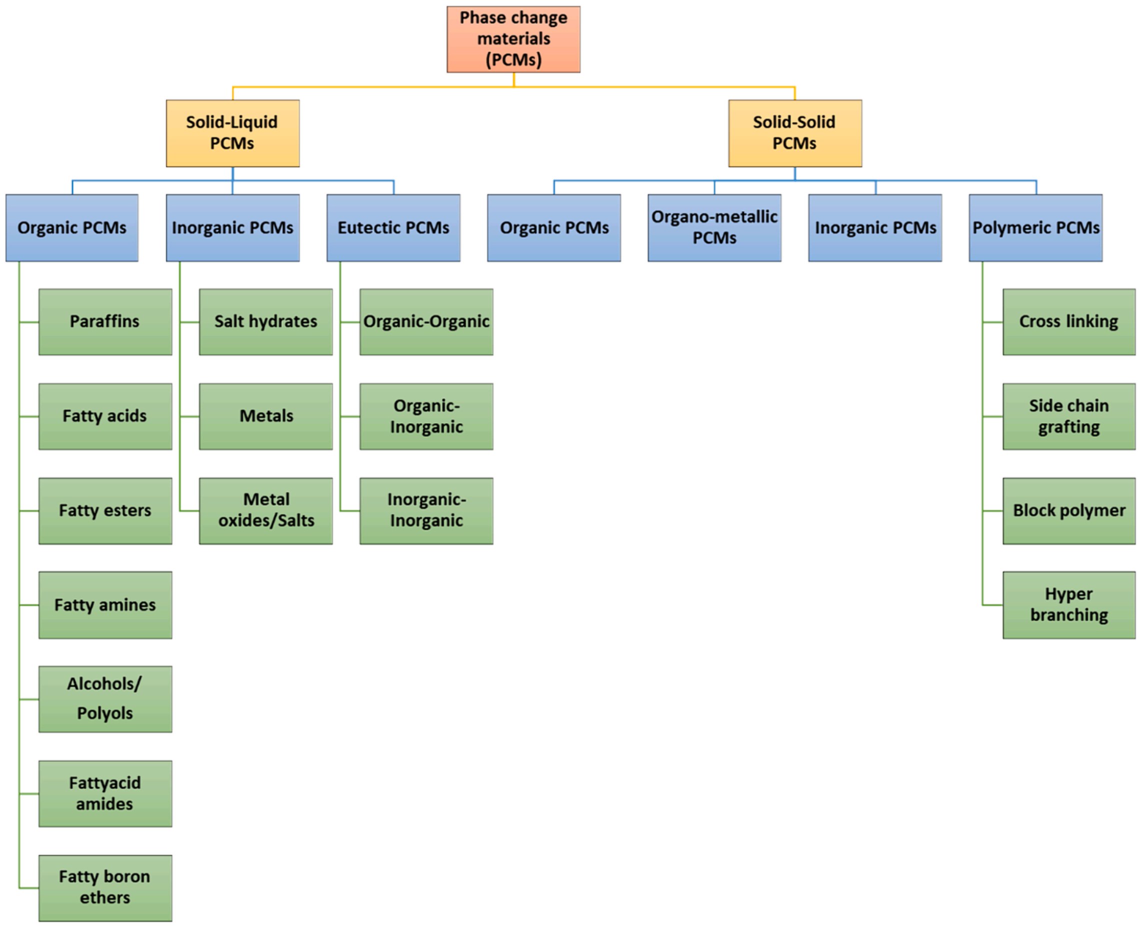

Fig. 2. The broad classification(up-to-date) of the phase change materials based on their phase change behavior and composition.

applications, such as building insulation, thermal energy storage for solar power generation, and temperature stabilization in electronic devices.

3. Applications of phase change materials

Phase change materials (PCMs) are utilized in many industries to store and release thermal energy during phase changes, enabling a multitude of applications. Several notable applications of PCMs encompass: (a) buildings and construction, (b) automobiles, (c) health care, chemical and pharma(drug), (d) solar energy storage, (e) electronics cooling, (f) power generation, (g) food and beverages, (h) water treatment(desalination), (i) textiles, (j) waste heat recovery. The literature reports published on various applications of the phase change materials are shown in Fig. 4. According to Fig. 4, the primary applications of PCMs are in buildings, with solar energy storage applications following closely behind. Research articles on PCM applications for water treatment (desalination), healthcare and pharmaceuticals (drug), and food applications are comparatively less prevalent.

3.1. Buildings and construction

Phase Change Materials (PCMs) are employed in various building materials to augment energy efficiency and boost thermal comfort. Within the construction field, phase change materials (PCMs) are included in different building materials such as gypsum boards, plaster, walls, bricks and concrete. The building components upgraded with phase change materials (PCM) serve as thermal mass, effectively absorbing surplus heat during the daytime and releasing it during the nighttime. This phenomenon contributes to stabilizing indoor temperatures and diminishes reliance on mechanical heating and cooling systems. Phase change materials (PCMs) are commonly incorporated into roofing, flooring [52], and attic insulation systems to mitigate heat gain within attics, reducing cooling requirements. Moreover, phase change materials (PCMs) are present in energy-efficient windows, facilitating the storage of surplus solar heat throughout the day and subsequent release throughout the night. This mechanism effectively diminishes the requirement for heating. PCMs can also be incorporated into the wall paints, acting as insulation for heat transfer across the walls. Incorporating phase change materials (PCMs) into building components is a sustainable and innovative strategy for optimizing energy utilization, improving thermal efficiency, and creating more comfortable living and working environments. The building components that can take PCMs are shown in Fig. 5.

Jiang et al. prepared a novel PCM composite to replace sand in building construction using porous titanium-bearing blast furnace slag (Ti-BFS) as support material and paraffin PCM for making a thermal energy storage cement. Further, the PCM composite was coated with epoxy resin to avoid PCM leakage. The composite showed excellent compatibility with cement and good thermal energy storage capabilities, with a paraffin loading rate of 21.9 %. Properties of cement, like thermal conductivity and density, were reduced compared to pure cement with the addition of PCM composite. The thermal energy storage capacity of cement is increased with the addition of PCM composite latent heat 65 J/g.

Frahat et al. prepared a based PCM composite using stearic-capric acid eutectic PCM and wood fibers for applying as thermal insulation in buildings. The composite was tested for four different climate zones of Turkey with one city from each climate zone, Ankara, Istanbul, Erzurum and Antalya, to understand the effect on fuel, cost and carbon emission

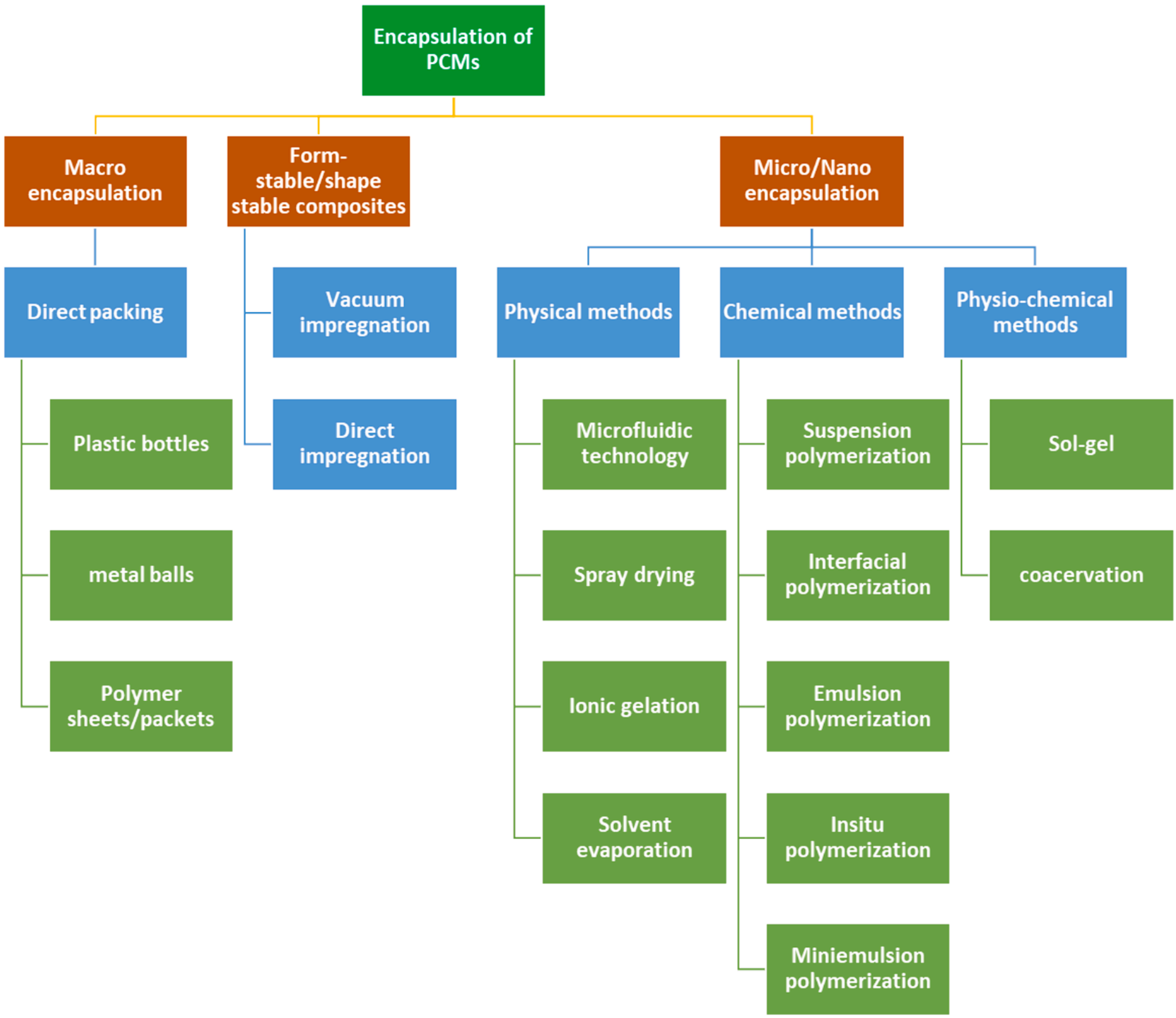

Fig. 3. The classification of encapsulation methods for phase change materials.

savings. The maximum PCM loading into the wood fibers was 52 wt% without leakage and an enthalpy of 92.1 J/g. The PCM composite could provide annual energy savings of 21 kWh/m^2 with 52.7 % yearly energy savings using 0.1 m thick PCM composite insulation. Maximum carbon emission reductions are noted with coal as fuel, and an 18.1 kg CO_2/m^2 reduction was noted in Istanbul. The payback period for PCM composites varied from 0.37 to 5.81 years, depending on the fuel and location.

Yang et al. research looked at applying hybrid nanoparticles (CuO + Al_2O_3) enhanced paraffin phase change material (Nano-PCM) in double-glazed windows, emphasizing energy savings, thermal comfort, economy, and daylighting. Numerical simulation results demonstrated that adding hybrid Nano-PCM enhanced windows' thermal inertia and insulation, although overheating might impact thermal comfort and natural illumination. The maximum temperature deviation noted using the PCM window was 9.31 °C. The best performance is obtained using CuO: Al2O3 ratio of 4:6, resulting in 2552 kJ/d energy savings and 2003 CNY during the window's life.

An encapsulated PCM containing eutectic hydrated salt as PCM and UV-curable polyurethane acrylate resin as shell material was prepared by Jia et al. for addition to cement. Further, modified graphene oxide (GO) was added along with PCM capsules into the cement to prepare thermal energy storage cement. GO addition improved the 28-day compressive strength of 20 vol% encapsulated PCM-added cement by 25 %. The addition of GO improved the cement's mechanical strength and heat transfer efficiency as the GO-PCM-composite cement possessed a denser interface transition zone and lower harmful porosity because of the excellent compatibility between the cement matrix and encapsulated PCM.

For use in construction applications, Nazari et al. investigated the preparation, characteristics, and integration of ethyl palmitate (EP) as a bio-based phase change material (BPCM) in wood particles that bound using 37.5 % epoxidized linseed oil (ELO) as binder. The optimum PCM content in composite was found to be 25 %. Compared to a reference composite without BPCM, the findings showed superior moisture buffer values, considerable thermal mass, the capability to store excessive latent heat, high thermal stability, and an improved specific heat capacity.

Waste swine sausage frying fat (melting temperature 32 °C, melting enthalpy 20 J/g) made up of saturated and unsaturated fatty acids was investigated by Bragaglia et al. as a sustainable PCM for building

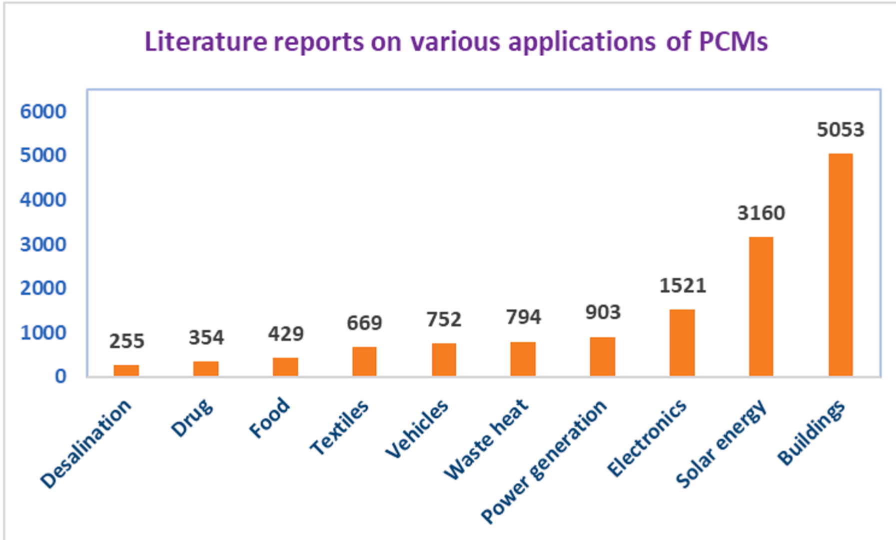

Fig. 4. Trends of literature on phase change materials application in various industrial sectors (.
Source: scopus.com, search phrase: "phase change materials" "keyword given on figure for application") [51]

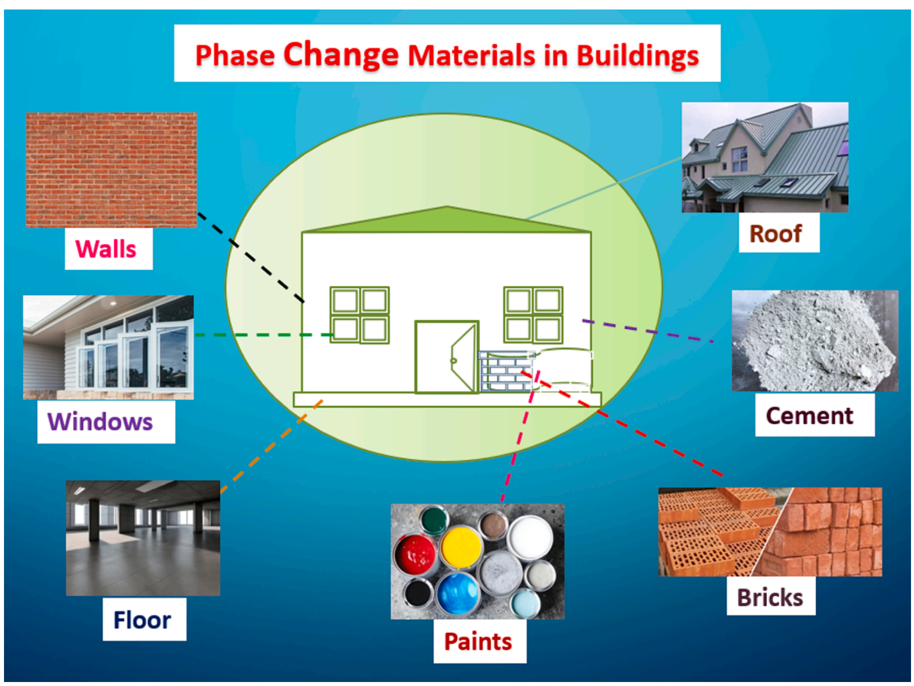

Fig. 5. Schematic diagram illustrating the integration of Phase Change Materials (PCMs) into various building components.

application. Two porous materials, i.e., polypropylene non-woven mat constructed from repurposed surgical mask filters and bio silica, were used to encapsulate the PCM for passive cooling applications in buildings. Application of PCM composite in a building wall through numerical simulations found to transfer thermal power of 10.2 W/m^2 per unit area of the wall, which was 37 % less than the standard building wall, which suggests that used cooking oil might be a fantastic option for circular economy strategy and an eco-sustainable solution for building cooling.

Yunlong et al. prepared a microencapsulated PCM containing discarded cooking oil containing methyl palmitate as PCM. The MPCMs with size 100 μm – 200 μm could regulate the temperature of the building wall due to their phase change properties of 20 °C and 68 J/g. Infrared thermal imaging experiments showed that 10 % MPCM-incorporated foam concrete can maintain a 4—5 °C temperature difference from the surrounding air.

Jeong et al. created a dry floor system by combining activated carbon (AC) with n-docosane to generate a PCM composite. After utilizing PCM composite, which had an enthalpy of 92.8 J/g in the dry floor heating system, a rapid rate of surface temperature increase was observed, which was a time-lag effect. It reduced the electrical energy consumption for heating than other floor heating systems.

By employing capric acid (CA) and ethyl alcohol to impregnate expanded vermiculite (EV) under vacuum, Dora et al. evaluated the viability of using an organic PCM composite in cement mortar. The findings revealed that the partial addition of nano-silica and coir fiber to the cement boosts the mortar boards' physical and mechanical strength. The addition of PCM composite improved the thermal properties of cement boards. The 5 % added nano silica and coir fiber combination to the PCM mortar board showed strong thermal resistance and enhanced thermal comfort in structures.

Phase change materials (PCM) were used in the paint mixture by Atiganyanun et al. to improve cooling performance in buildings. Capric acid PCM was sol–gel encapsulated inside silicon dioxide, and barium sulfate was used as paint pigment. Paints have a higher adequate heat capacity when PCM is applied at a given total particle volume concentration, but the solar reflectance decreases as the PCM volume concentration increases above 0.25. According to this study, PCM components can help radiative cooling paint systems that have trouble reaching sub-ambient cooling.

A summary of various research studies on the application of PCMs in various building components is provided in Table 2.

Summary

PCMs could be integrated into various building components like windows, walls, roofs, paints, bricks and floors. The PCM integration into building components could reduce the ambient temperature of the building compared to its surroundings by an average of 4–5 °C. Studies showed it could reach a maximum temperature difference of 9 °C. Further, the energy consumption of the buildings was also reduced with the integration of PCMs annually by 20–50 %. BioPCMs and waste-derived PCMs also have good potential for application in thermal regulation and building energy savings. PCMs also reduce the heat transfer through the building components and increase the thermal comfort inside buildings. There are a few drawbacks to integrating PCMs in building components, like reduction in mechanical strength properties of the mortar and bricks, visual properties of paints, extra space occupation in case of walls and floors, leakage issues during phase change and incomplete utilization of phase changeability.

3.2. Automobiles

Automotive applications for phase change materials (PCMs) include electric vehicles (EVs), refrigerated trucks and hybrid vehicles. In EV battery packs, PCMs can be employed for heat management. PCMs assist in keeping the battery within its ideal temperature range during the charge and discharge cycles, extending its life and improving performance. Additionally, PCMs are used in cabin comfort systems. When temperatures are high, PCMs can help maintain a comfortable interior temperature by decreasing the energy demand on heating and cooling systems. This increases overall vehicle efficiency and range. PCMs are also being explored to provide an anti-freezing effect in vehicle tires for extreme winter conditions. In hybrid cars and refrigerated trucks, PCMs help to insulate heat transfer from hot surroundings and collect the waste heat produced by braking and engine running. Recovered heat can be stored in PCM to warm the cabin or supplement engine power on subsequent starts, lowering fuel use and pollutants. Modern automobile systems' energy efficiency and thermal performance are significantly improved by PCMs. The application scope of PCMs in various parts of automobiles is shown in Fig. 6.

To enhance battery thermal management (BTM), Li et al. suggested phase change material (PCM) cooling for autonomous underwater vehicles (AUVs). This study evaluated many elements, including PCM thickness, eccentricity, and melting properties. The findings demonstrated that PCMs work effectively in the thermal control of AUV batteries, with an ideal eccentricity of 10 mm.

Utilizing PCMs (RT35, RT50) and thermoelectric coolers (TEC), Pakrouh et al. created a novel liquid cooling system that managed the temperature of the TEC's hot side. The fluid flow rate, TEC number, and input electrical power were all considered while assessing the system's performance. According to the study, RT35 maintained the battery pack at a lower temperature than RT50 under identical circumstances because of its lower phase transition temperature.

Sun et al. used various models to study a composite battery thermal

Table 2
Summary of Reports Discussing the Effectiveness of PCMs in Various Building Components.

Author	PCM/shell	Method of encapsulation/ Application building component	Properties (Melting peak temperature, Enthalpy)	Remarks
Jiang et al. 2023 [53]	Paraffin/Titanium bearing blast furnace slag	Vacuum impregnation/ mortar	33.8 °C, 65.7 J/g	Reduced the temperature fluctuations of the building and increased energy efficiency
Frahat et al. 2023 [54]	Eutectic PCM of capric and stearic acid/wood fiber	Impregnation/ walls-ceiling-floors	23.4 °C, 92.1 J/g	52.7 % energy savings were noted using 0.1 m thick wood fiber PCM composite used in buildings
Yang et al. 2023 [55]	Hybrid PCM containing Paraffin with nano Al_2O_3-CuO	Double glazed window	18 °C, 205 J/g	Temperature deviation of 9.31 °C obtained using PCM
Jia et al. 2023 [56]	$Na_2HPO_4{\cdot}12H_2O$-$Na_2CO_3{\cdot}10H_2O$/UV-curable polyurethane acrylate resin/ graphene oxide	UV-curation-mixing-vacuum filtration/Mortar	84.45 J/g	GO modified encapsulated PCM incorporation increased compressive strength of mortar and thermal energy storage capacity
Nazari et al. 2023 [57]	Ethyl palmitate/wood particles	Vacuum impregnation followed by cold compression molding/ walls and roof of building	18 °C-25 °C (melting range)/ 45 J/g	Biobased ethyl palmitate PCM composite with wood particles acted as good insulation in buildings
Bragaglia et al. 2023[58]	Waste fat from pork meat cooking/ two supports (i) diatomite and (ii) polypropylene mat taken from surgical mask	Vacuum impregnation/exterior building wall	Two peaks at 0 °C, 30 °C, 20 J/g	PP filter mask composite PCM had better impregnation ratio of 75 % and reduced 38 % of transmitted thermal power in building model
Yunlong et al. 2023[59]	Microencapsulated methyl palmitate derived from waste cooking oil/silica	Suspension polymerization/Foam concrete	19.61 °C (onset), 70.02 J/g	Concrete with 5 % and 10 % MPCM showed 2.8 °C and 3.9 °C lower temperature than reference during heating
Jeong et al. 2023 [60]	n-docosane /activated carbon (D-HSA)	Vacuum impregnation/dry floor heating	43.46 °C, 92.10 J/g	PCM dry floor heating system consumed less electrical energy than the general dry and wet floor heating systems
Dora et al. 2023 [61]	Capric acid-ethyl alcohol/ expanded vermiculate	Vacuum impregnation/cement mortar	32.04 °C, 34.08 J/g	PCM composite mortar had good mechanical, durability, and thermal regulation qualities for maintaining building thermal comfort
Atiganyanun et al. 2023[62]	Capric acid/silicon dioxide	Sol-gel/ building paints	33.5 °C, 73.3 J/g	Inclusion of the PCM reduced the heat load in the paint and consequently enables sub-ambient cooling

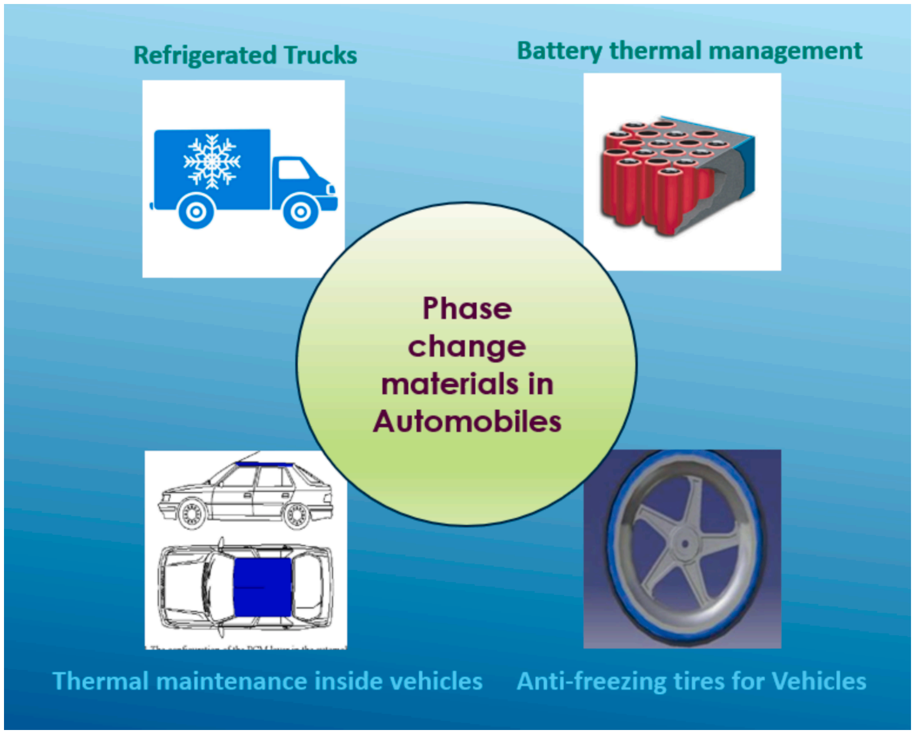

Fig. 6. Phase Change Materials (PCMs) for Thermal Management in Automobiles.

management system (BTMS) for electric cars, taking into account the temperature outside, discharge rates, the components of the phase change materials, intake mass flow rates, and coolant temperature. According to the findings, a battery thermal management system that combines liquid cooling and phase change materials performs better than one that solely uses liquid cooling. Paraffin PCM with 10 % expanded graphite showed better performance for BTMS. Further, an increase in mass flow rate or decrease in coolant flow temperature also decreased the maximum temperature of the battery pack.

There are several concepts like passive, active and hybrid cooling for BTMS to keep T_{max} and temperature difference between charging/discharging (ΔT) within acceptable limits. In their study, Isfahani et al. developed a hybrid cooling system employing metal foam, micro-channels, and phase change materials (PCM). They compared its performance with that of active and passive systems. Following the findings, passive BTMS (PCM/metal foam) had a higher T_{max} (319 K), a better temperature distribution, and a smaller ΔT (1 K), while the T_{max} of active BTMS (microchannels) was lower (312 K) but the ΔT was higher (9 K). The hybrid system developed in this study had a T_{max} of 308.4 K and ΔT of 3.4 K.

Gurbuz et al. designed a latent heat thermal energy storage system (LHTES) using PCM augmented with Al_2O_3 nanoparticles to capture heat energy discharged by ICE car exhaust gases. In cold weather, the performance of the LHTES system was evaluated for interior heating of a typical sedan car using RT55 paraffin wax as PCM. The results demonstrated that the cabin temperature could be raised by around 29 % while the solidification process was significantly enhanced by using Al_2O_3 up to 10 % weight fractions into PCM.

Sood et al. used computational fluid dynamics simulations to assess the performance of the four PCMs OM 29, HS 24, Bio Q27, and CaCl2··6H2O for thermal regulation of vehicle cabin for a short time of 120 s. The PCM incorporation in the cabin led to a 7-degree drop in cabin temperature in 120 s. Of the four investigated PCMs, CaCl2··6H2O was the most effective, leading to a ~ 33 degrees reduction in peak cabin temperature when the operating period is extended to one hour.

Phase change materials (PCMs) in various angles are employed inside tires by Ramana et al. to address the clogging of ice on vehicle tires in cold weather situations. PCMs produce tremendous amounts of heat when they freeze and absorb tremendous amounts of heat when defrost. They discovered that when positioned at 360 degrees or surrounding a tire's inner wall, PCMs are pretty effective at transferring heat to tires in cold weather.

The roof and the gaps behind a vehicle's doors were filled with coconut oil, an organic PCM by Afzal et al., to analyze the capability of PCM to maintain cabin temperature in the human comfort range. Regression modeling employing multiple feed-forward-back propagation (MBP) artificial neural networks was used for the study. The Response Surface Methodology (RSM) was applied to optimize variable effects. The results demonstrated that by employing PCM, the inside temperature of the vehicle cabin was decreased by ~ 13 °C with an average increase in relative humidity of 8.6 %.

Sangeetha et al. studied the effect of a cooling system containing natural wax PCM with a melting point of 36 °C surrounded by water in copper coils to regulate the interior compartment temperature of an automobile held still and exposed to solar radiation from the sun. Employing PCMs as a heat-reduction and air-cooling system prevented an excessive rise in cabin temperature and ensured thermal comfort within the automobile.

Saleel et al. conducted three-month experiments by implanting coconut oil as PCM beneath the vehicle's roof to regulate cabin temperature in the Abha region, Saudi Arabia. The initial monitoring of cabin temperature without a PCM produced data primarily consistent with the theoretical values in the literature. PCM reduced the maximum temperature inside the cabin by 15 °C.

The various literature summarizing the application of PCMs for thermal management across various automobile components is shown in Table 3.

Summary

PCMs in automotives can be mainly used for thermal management of batteries, thermal regulation of vehicle cabins, de-icing of tires and recovering heat generated from combustion engines. The application of

Table 3
Summary of Literature on Using PCMs for Automotive Thermal Management.

Author	PCM/shell	Method/application	Properties	Remarks
Li et al. 2023 [63]	RT 35	PCM jacket for thermal management of battery in autonomous underwater vehicle	35 °C, 160 J/g	16 mm thick PCM layer showed excellent thermal performance
Pakrouh et al. 2023[64]	RT 35, RT 50	PCM enhanced battery thermal management system	RT 35—36 °C, 170 J/g RT 50—51 °C, 160 J/g	RT35 keeps the battery pack at a lower temperature than RT50 due to its lower phase change temperature
Sun et al. 2023 [65]	Paraffin wax with 10 % expanded graphite	PCM with liquid cooling for thermal management in electric vehicles	32–36 °C, 206 J/g	Composite BTM system with PCM and liquid cooling could reduce maximum temperature and perform well than only liquid cooling
Isfahani et al. 2023[66]	RT27/ aluminum foam	Hybrid PCM based BTMS	27 °C, 179 J/g	Using PCM BTMS the maximum temperature is 35.25 °C and max ΔT is 3.4 °C
Gurbuz et al. 2022[67]	RT 55-Al_2O_3 nanoparticles mixture	PCM tank for heating car cabin in cold conditions	55 °C, 170 J/g	10 wt% Al2O3 addition to PCM showed better performance
Sood et al. 2021 [68]	OM 29, HS 24, Bio Q27 and $CaCl_2$. 6 H_2O	PCM layer/ Roof top of the car	OM29- 29 °C, 194 J/g HS 24—25 °C, 185 J/g Bio Q27- 27 °C, 230 J/g $CaCl_2{\cdot}6H_2O$- 30 °C, 187 J/g	$CaCl_2{\cdot}6H_2O$ found best out of four PCMs with 33 K temperature reduction
Ramana et al. 2021[69]	OM-11/ small tough envelopes	PCM envelopes arranged on inner walls of vehicle tires	12 °C, –-	PCM is quite effective and efficient in transfer of heat to tires in cold conditions when positioned at 360°
Sangeetha et al. 2021[70]	Natural wax/PCM module with copper pipes	PCM bag attached to roof of car	36 °C, 157 J/g	PCM applied could help in maintaining cabin temperature at 36 °C
Afzal et al. 2020 [71]	Coconut oil/extra Fine rubber sheets	PCM pouches kept at roof top of car and vacant spaces in door interiors	21–25 °C, 103.35 J/g	17.15 °C maximum temperature reduction observed by employing PCM
Saleel et al. 2019 [72]	Coconut oil/thin rubber sheet pouches	PCM pouches/ roof top of car	22–24 °C, 103.25 J/g	1.43 kg coconut oil as PCM could reduce about 15 °C in the cabin temperature, compared without PCM in summer

PCMs for battery thermal management systems (BTMS) is picking up due to the increased usage of electric vehicles. The phase change materials considerably help in the thermal management of batteries, but hybrid systems combining PCMs with liquid cooling or air cooling are better than only PCM systems. The lower melting PCMs (around 30 °C) performed better in BTMS than higher melting PCMs. Further, the heat recovered from the ICE engine could raise cabin temperatures by 29 % using PCMs compared to cases without PCM in colder conditions. The inorganic salt hydrates performed better than organic PCMs when PCMs of the same melting point were used for cabin thermal regulation. The employment of PCMs works effectively in vehicle cabins and has been found to reduce the peak temperatures of cabins by an average of 13–15 °C. The PCMs can address the ice-clogging issue with vehicle tires in colder climates. The PCM arranged inside vehicle tires around a 360° radius effectively reduces the ice clogging on tires.

3.3. Health care and pharma

In the healthcare and pharmaceutical sectors, phase change materials (PCMs) are promising, especially for temperature-sensitive medical and diagnostic items. For things like vaccinations, blood products, pharmaceuticals, and diagnostic reagents, PCMs help maintain stable temperatures. They are incorporated into cold chain delivery systems, vaccination carriers, and storage containers. Additionally, PCMs are used in temperature-sensitive medical equipment and portable coolers for organ transportation and neonatal babies. PCMs help maintain the quality and safety of essential medical treatments and supplies by providing accurate heat control. Drug delivery systems can use phase change materials (PCMs) to regulate medication release. PCMs enable precise, time-released drug administration by storing and releasing medications at particular temperatures. In pharmaceutical applications, this can increase patient compliance and lessen adverse effects. By preserving a constant temperature environment, PCMs can improve sensor performance. They control temperature variations in sensor systems to ensure reliable and consistent data. In applications like medical equipment and scientific instruments, temperature management is critical for accurate and reliable data capture, which is especially important. The application scope of PCMs in various biomedical applications is shown in Fig. 7.

Nanocatalytic treatment is recognized as a promising method for treating cancer. However, their catalytic activity is often constrained by the tumor microenvironment's low endogenous hydrogen peroxide (H2O2) levels. Due to their excellent near-infrared (NIR) photothermal conversion efficiency, carbon vesicle nanoparticles (CV NPs) were chosen by Xu et al. as carriers. The platinum iron alloy nano particles (PtFe NPs) were grown in situ on CVNPs and used for encapsulating PCM and the drug lapachone (La). These multifunctional nanocatalysts could exhibit a triggered photothermal effect and result in the release of the drug La. Due to tumor-specific H_2O_2 amplification and mild-temperature photothermal therapy, this multifunctional nanocatalyst may be a versatile therapeutic agent that works synergistically with NIR-enhanced nanocatalytic tumor therapy.

Lu et al. combined mesoporous carbon nanoparticles (MCN) with stearic-lauric eutectic PCM for the "on-demand" release of the poorly soluble medication mercaptopurine (MP). The eutectic PCM with a melting temperature 40 °C acted as a gatekeeper for holding MP inside carbon nanoparticles and stopped the prerelease of the drug at body temperature conditions. The PCM facilitated the drug release only after reaching the temperature over its melting point under NIR irradiation. The NIR-triggered drug delivery capabilities and photothermal effect of the designed drug delivery system enhanced the antitumor activity.

Ye et al. created an effective antibacterial hydrogel composite with a dependable NIR-triggered release of the drug rifampicin using alginate and nanotubes. The composite was made by combinedly encapsulating rifampicin drug, NIR absorbing dye indocyanine green (ICG), fatty acids based eutectic PCM into halloysite nanotubes. Eutectic PCM with a

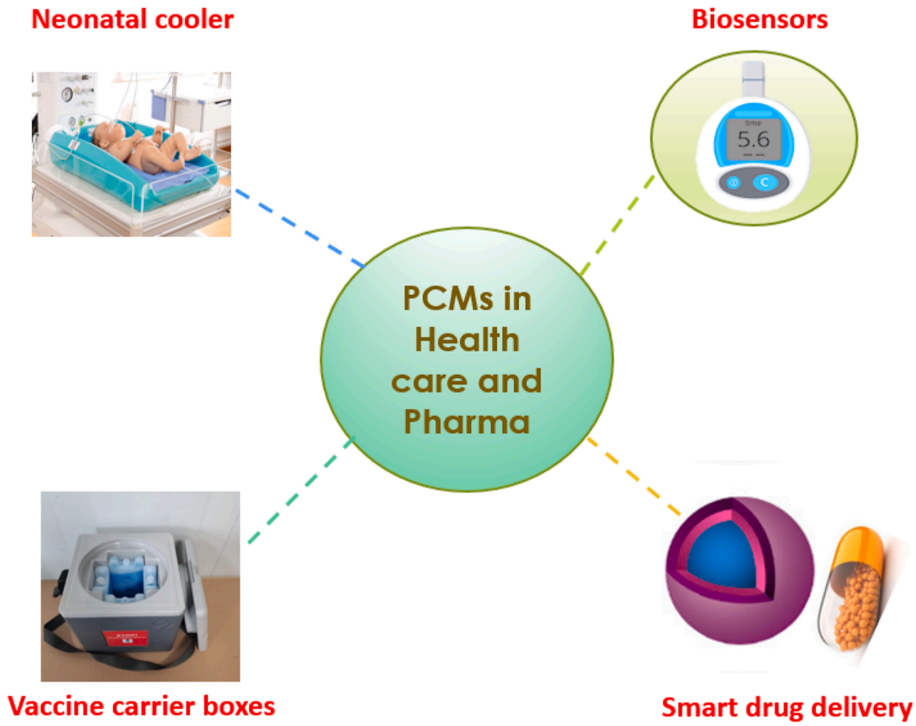

Fig. 7. Schematic illustration of Phase Change Materials (PCMs) in Healthcare and Pharmaceuticals.

melting temperature of 39 °C served as a gate to facilitate NIR-triggered drug release. Applying NIR-triggered composite hydrogel to a bacterial-infected rat inhibited the bacteria colonization, reduced the inflammatory response of bacteria and enhanced the regeneration of the wound by promoting collagen and angiogenesis deposition.

To accomplish chemotherapy synergized by dual-enhanced phototherapy of breast tumors, Wang et al. created a new phase change material (PCM)-based nano platform that co-delivers paclitaxel (PTX), IR780 and gambogic acid (GA) simply. PCM-based nanoparticles (NPs) showed favorable particle size and greatly improved photostability of IR780. PCM endowed the NPs with hyperthermia-triggered release of PTX for chemotherapy, which was beneficial in dampening the side effects. PTT-activated low-dosage PTX-based chemotherapy and dual-energized phototherapy have shown exceptional antitumor efficacies both in vitro and in vivo.

Using zeolitic imidazolate framework-8/polylactic acid (ZIF-8/PLA) electrospun fibrous membrane nanocarriers, Zhang et al. successfully encapsulated the phytochemical curcumin (Cur) and ICG before covering them with phase-change material (PCM) through noncovalent interactions. The Cur-ICG@ZIF-8/PLA/PCM (CIZPP) composites exhibited photothermal, photodynamic, and chemo-killing characteristics. Dual stimuli-responsive (NIR and pH) release of curcumin from CIZPP was made possible by combining the PCM's NIR-induced phase shift mechanism with the dissociation of ZIF-8 in an acidic environment created by bacterial infection. Experimental data from both in vitro and in vivo investigations shows that CIZPP can halt the spread of drug-resistant bacteria by irreversibly damaging the cell membrane.

Phase change material (PCM) and bio electrocatalytic materials were used by Sun et al. to create a thermal self-regulating intelligent biosensor that improves biosensing detection for glucose testing across a wide temperature range. An electroactive PCM-based system was prepared by first microencapsulating PCM docosane core in SiO_2 shell, followed by the deposition of polydopamine and carbon nanotubes as an electroactive layer on SiO_2 shell. The electroactive PCM microcapsules showed a distinct core–shell architecture and were all consistently spherical. They created an electrochemical biosensing system by employing the acquired electroactive microcapsules and glucose oxidase as a redox enzyme. The intelligent biosensor microcapsules with 137 J/g enthalpy showed a superior determination capability and better detection performance towards glucose than conventional biosensors in a high-temperature region, with a high sensitivity of 5.95 $\mu A \cdot mM^{-1} \cdot cm^{-2}$ and a lower detection limit of 13.11 μM at 60 °C.

To create an intelligent nanoplatform, dendritic mesoporous organosilica nanoparticles (DMONs) were employed by Hu et al. and 1-tetradecanol (TD) as PCM with PEG as a dispersing agent. The chemotherapeutic medicine cisplatin and the color ICG were combined to generate the compound DMON-PEG-cisplatin/ICG-TD (DPCIT). The findings show that DPCIT effectively kills cancer cells and slows tumor growth when exposed to laser irradiation. In contrast to the apparent liver damage brought on by cisplatin therapy alone, the novel nano platform shows less systemic toxicity in in-vivo testing.

PCM and polydopamine (PDA) were concurrently coated on imidacloprid (IMI) loaded mesoporous nano silica (MSN) particles by Yu et al. to achieve NIR-triggered IMI release. The best PCM for striking a compromise between high thermal stability and delicate thermal responsiveness was found to be myristyl alcohol (MA). With a maximum temperature rise of 23.3 °C (808 nm, 2 W/cm^2, 300 g/mL), MSNs@MA-PDA nanocomposites demonstrated sustained photothermal conversion capacity that was concentration and irradiation power dependent. Drug loading and encapsulation efficiency were 30.1 % and 43.0 %, respectively, according to IMI. When the temperature was raised from 25 °C to 38 °C, there was an approximately 30 % increase in the cumulative release of IMI from IMI@MSNs@MA-PDA.

Dixit et al. used expanded graphite (EG) as the supporting matrix and isopropyl stearate (IPS) as the PCM to build a vaccine box. Five composites were created using differing amounts of EG in various ratios and a constant loading of IPS. The composite had a max core content of 88 wt % with an enthalpy of 172 J/g and melting point onset of 6 °C. By placing the PCM-composite in a vaccine carrier box and subjecting it to three distinct temperatures, 30 °C, 40 °C, and 50 °C as well as a real-time application being exposed to the sun and found that the PCM composite is effective in maintaining the temperature of vaccines and other products below 15 °C.

Glauber salt solution can serve as a PCM solution that can be used therapeutically to maintain the temperature of neonatal babies who are experiencing oxygen deprivation just after birth or within six hours. Olsan et al. produced PCMs at all required temperatures in the 20——32 °C range by varying the salt fraction in the solution.

Table 4 presents a summary of literature reports discussing the application of PCMs in various biomedical applications.

Summary

PCMs are effective for use in health care and pharma industries for various applications such as vaccine transportation, designing drug delivery systems for cancer treatment, and designing neonatal coolers. PCMs are very useful in designing drug delivery systems for cancer treatment for various drugs like lapachone, mercaptopurine, rifampicin, paclitaxel, cisplatin, etc., through various drug-releasing mechanisms. The stearic-lauric acid eutectic PCM was used to design drug delivery systems. PCMs like 1-tetradecanol, 1-hexadecanol, and oleic acid mixtures are also used to design drug delivery systems. Fattyacid/alcohols based PCMs may be chosen for the drug delivery system development due to their human-friendly nature. Further, PCMs like docosane were used to enhance the performance of biosensors for glucose detection. Myristyl alcohol was found to be better than tridecyl and pentadecyl alcohols for the triggered pesticide delivery system of the imidacloprid pesticide. Isopropyl stearate PCM composite showed promising thermal buffering capacity for maintaining the temperature of the vaccine box. Glauber salt solution with a 20–32 °C phase change range was suitable for neonatal cooler design.

3.4. Solar energy storage

Phase change materials (PCMs) are crucial in solar energy storage applications to handle the intermittent nature of solar electricity. They are incorporated into solar thermal and concentrated solar power (CSP) facilities. During sunny periods, concentrated solar collectors produce extra heat stored by PCMs. The PCM releases stored heat to power steam turbines or generators to generate electricity, allowing for continuous power output even when the sun isn't shining or energy demand is at its highest. The addition of PCMs increases the general effectiveness of solar equipment and systems. The performance and efficiency of solar thermal systems can be maximized by using PCMs, which allow for more effective energy capture and storage. The capability of PCMs utilizing for various solar energy storage applications is shown in Fig. 8.

Liu et al. developed a flexible multi-functional composite PCM film using interwoven carbonized bamboo fibers (CBF), polyvinylidene fluoride (PVDF), and paraffin PCM for electrosolar thermal conversion applications. The films have impressive long-term cycle stability, significant heat storage capacity (≥103.6 J/g), and noteworthy flexibility. The film's potential for solar-thermal conversion was expanded by incorporating $Ti_3C_2T_x$ as a photon-capture and heating molecule.

Using a microfluidic encapsulation technique, Hu et al. produced a unique phase change heat storage microcapsule for solar thermal energy storage that can retain up to 171.8 J/g, or more than 88 % of its latent heat. Microcapsules were prepared using paraffin PCM and calcium alginate shell. CFD modeling demonstrated that the low heat transfer efficiency of PCM capsules may be increased by optimizing the geometrical design of the microcapsules, which significantly improves heat transmission.

Using stearic acid (SA) as the phase change material and stearic acid-modified MOF (HS) with CuO produced from MOF (HS@CuO composites), Yan et al. developed novel metal–organic framework (MOF)-based phase change composites. The composites demonstrated exceptional form stability and thermal storage capacity, with a loading rate of 71.8 % and a thermal storage capacity of 158.24 J/g. The SA/HS@CuO composites also demonstrated enhanced thermal conductivity and outstanding solar thermal conversion performance, highlighting their potential for solar energy management, thermal storage, and usage.

Fan et al. developed a simple, scalable PCM-based device that simultaneously improves heat transmission and light absorption for solar water heating applications. Compared to the original composite and the MWCNT-doped composite, the PCM-based system with MWCNT and fins raised the water's temperature by 58.6 % and 55.2 %, respectively. The maximum thermal efficiency of the suggested system is up to 89.2 %, exceeding that of most flat plate and tube solar collectors.

Han et al. created MnO_2-decorated double-shell microencapsulated PCMs using electrochemical adsorption and the redox approach. N-octadecane was taken as PCM, the first polymeric shell was prepared using melamine formaldehyde, and the second was metal oxide, i.e., MnO_2. The enthalpy value of the double-shell microcapsules ranged from 133.56 to 152.71 J/g, and their encapsulation ratio was greater than 56 %. After 100 heat cycles of testing, the microencapsulated PCMs demonstrated good thermal cycling stability. The excellent optical and electrochemical properties of MnO_2 helped the microcapsules to have 93 % light-to-heat conversion efficiency and a specific heat capacitance

Table 4
Summary of the application of PCMs in the healthcare, chemical and pharma industry.

Author	PCM/shell	Method/application	Properties	Remarks
Xu et al. 2023[73]	Lauric and stearic acid eutectic PCM	Thermal responsive drug carrier	39 °C	PCM based nano catalytic drug carrier for controlled drug release and enhanced catalytic therapy
Lu et al. 2023[74]	Stearic acid and lauric acid eutectic mixture	Precise release of mercaptopurine at tumor sites	40 °C	PCM based NIR triggered drug release promoted the antitumor activity
Ye et al. 2023[75]	Lauric acid-stearic acid (4:1) mass ratio mixture	Release of antibacterial drug rifampicin	39 °C	PCM gated nano capsules showed multi stage drug release under IR radiation
Wang et al. 2023[76]	1-hexadecanol and oleic acid mixture 3.5:1 wt ratio	Control release of Paclitaxel drug used for treating breast cancer	46 °C	PCM based codelivery nanocarriers for chemotherapy drug delivery
Zhang et al. 2022[77]	Lauric acid-stearic acid (3.5:1) mass ratio mixture	Non covalent interactive PCM dip coating on potent antimicrobial material	46 °C	PCM coated pH/NIR dual sensitive intelligent antibacterial materials
Sun et al. 2022[78]	n-docosane/SiO2	Interfacial polycondensation/ electrochemical biosensor	46 °C, 138.5 J/g	PCM based biosensor for glucose detection is designed with enhanced performance
Hu et al. 2022[79]	1-tetradecanol	Cisplatin drug/indocyanine green release system based on PCM	39 °C	Efficient PCM loaded nano drug delivery system for cancer therapy
Yu et al. 2022[80]	Tridecyl alcohol (TA), Myristic alcohol (MA), 1-Pentadecyl alcohol (PA) and /mesoporous silica nanoparticles	Imidacloprid pesticide control release based on PCM	TA-33 °C MA-39.5 °C PA-44.5 °C	PCM based NIR responsive pesticide delivery system was developed with myristic alcohol as optimum PCM
Dixit et al. 2022[81]	Isopropyl stearate/expanded graphite	PCM based vaccine carrier box	6.1 °C, 172 J/g	4.15 h thermal buffering observed with PCM based vaccine box
Olson et al. 2022[82]	Glauber salt solution	Cooling for asphyxiated infants (neo natal babies)	20–32 °C	Appropriate composition of glauber salt solution found out for designing neonatal cooler

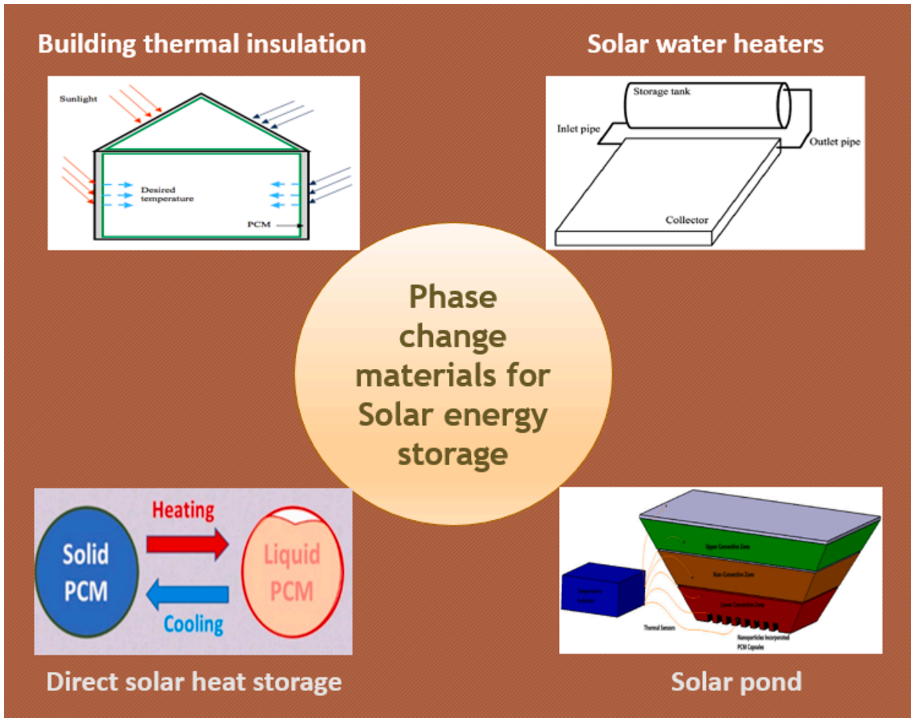

Fig. 8. The pictorial representation of the application of PCMs for solar energy storage.

of 364F/g.

The phase change material (PCM) composite using MOF-porous carbon materials created by Xiao et al. possesses excellent form stability, thermal conductivity, and photothermal conversion capacity. The composite used expanded graphite to minimize Zeolitic imidazole framework (ZIF) particle agglomeration and offer a high specific surface area and pore volume for paraffin wax adsorption. The composite exhibited a three-fold increase in thermal conductivity, a 95.56 % photothermal conversion efficiency, and outstanding form stability, highlighting the promise of MOF-enhanced PCM composites for thermal energy storage and renewable energy applications.

Calcium chloride and calcium fluoride eutectic combinations were explored by Jacob et al. as potential thermal energy storage materials for high temperatures. They discovered two storage options: peritectic, which occurs at 730 °C and contains 41 mol% calcium fluoride, and eutectic, which occurs at 647 °C and 18.3 mol% calcium fluoride. These eutectic PCMs could be cost-effective high-temperature storage mediums due to their high enthalpies (298–310 J/g) and heat capacities.

A unique kind of composite microcapsule with an n-Eicosane core and a TiO_2 shell modified with plasmonic TiC was created by Zhou et al. The microcapsules displayed strong full-spectrum absorption capabilities and high photo-thermal conversion efficiency (73.45 %). This work underlined the critical function of plasmonic TiC particles in the phase change microcapsules and offers a design method for full-spectrum solar-thermal conversion and storage applications.

An energy-efficient PCM-based solar cold storage system was developed by Natarajan et al. to preserve fruits and vegetables in remote agricultural areas. They discovered that keeping the product temperature within the permitted range for 20 h during a power loss resulted in considerable energy savings. Bananas may be kept at room temperature for 28–30 days because of PCM material's ability to hold onto latent heat and maintain temperature. PCM-based solar cold storage was reduced by 17.9 % energy consumption compared to standard solar cold storage.

By adding n-Eicosane into the carbonized watermelon peel (CWP) coated with MnO_2 nanosheets, Shuiab et al. created a low-cost, shape-stabilized, and Thermo conductive composite PCM. The PCM composites with 88 % core material loading had the potential for effective solar energy use and low-cost biomass waste applications. The composites had high enthalpy (220 J/g), high energy storage and conversion efficiency (94.5 %), hydrophobic and self-cleaning properties.

The summary of various application reports of the literature discussed is presented in Table 5.

Summary

PCMs could be used to store solar energy in the form of heat. The PCM composites with highly conductive materials showed a 70–96 % photothermal conversion efficiency. PCM composites with metal–organic frameworks, expanded graphite, manganese dioxide, and multiwall nanocarbon tubes showed photothermal conversion of $\sim \geq$ 90 %. In contrast, the composite made with titanium carbide/titanium dioxide showed a photothermal conversion of 73.45 %. The eutectic PCMs formed with calcium chloride and calcium fluoride, i.e., peritectic with 730 °C and eutectic with 647 °C, can be used in concentrated solar power plants for power generation. The PCM-integrated solar cold storage showed 17.9 % energy savings, and PCM will maintain the temperature inside cold storage during power cuts.

3.5. Electronics cooling

Electronics cooling applications use phase change materials (PCMs) to control and improve the thermal management of solar cells and electronic equipment. When operating, electronic components generate heat, which PCMs absorb and store. When the temperature rises above a set point, the PCM goes through a phase transition, absorbing the extra heat and preserving a constant temperature inside the device. To avoid overheating and ensure efficient and secure electrical functioning, the PCM releases the heat trapped when it cools and solidifies. This passive cooling technique improves the effectiveness and durability of electronic components, which also ensures dependable and long-lasting electronics by eliminating the need for active cooling devices like fans. PCMs could be used to store extra heat produced by servers in data centers. They take in heat and release it, decreasing the need for cooling systems that consume a lot of energy and improving energy efficiency. PCMs serve as power chip heat sinks, absorbing and storing extra heat to

Table 5
Applications of PCMs in Solar Energy Storage.

Author	PCM/shell	Method/application	Properties	Remarks
Liu et al. 2023 [83]	Film of Paraffin/inter woven carbonized bamboo fibers/poly vinylidene fluoride	Composite phase change film for solar electrical thermal energy conversion	57.2 °C, 103.8 J/g	Flexible PCM composite with Ti_3C_2 T_x film showed enhanced solar thermal conversion
Hu et al. 2023 [84]	Paraffin/Sodium alginate/$CaCl_2$	Microfluidic encapsulation/solar thermal energy storage	36 °C, 171.8 J/g	Paraffin microcapsules showed notable latent heat storage capability
Yan et al. 2023 [85]	Stearic acid/metal–organic framework/CuO	Vacuum impregnation/solar energy storage	52–55 °C, 158.24 J/g	95.9 % solar thermal conversion was noted with phase change composite
Fan et al. 2023 [86]	PEG6000/metal foams/multiwall carbon nanotubes	Vacuum impregnation/solar pond	57.5–64.5 °C, 179 J/g	PCM-based proposed system showed 89.2 % thermal efficiency
Han et al. 2023 [87]	n-octadecane/melamine formaldehyde/Manganese dioxide (MnO_2)	Insitu polymerization/ electro chemical adsorption and redox methods	29.97 °C, 136.99 J/g	Double shell capsules with 7 wt% MnO2 showed 93 % light-to-heat conversion with specific capacitance 364F/ g
Xiao et al. 2023 [88]	Paraffin wax/EG/ZIF-67	Vacuum impregnation	40 °C, 159.16 J/g	95.56 % light-to-heat efficiency was noted with metal–organic frame PCM-EG composite
Jacob et al. 2023[89]	Calcium chloride-calcium fluoride eutectic PCM	Concentrated solar power	Eutectic- 647 °C, 298–310 J/g Peritectic- 730 °C, 298–310 J/g	PCM for high-temperature thermal energy storage was designed for use in concentrated solar power plants
Zhou et al. 2023[90]	n-Eicosane/ titanium carbide/ Titanium dioxide	Sol-gel process/ photo-thermal conversion	44.19 °C,118.38 J/g	Eicosane-TiC-TiO2 capsules showed complete spectrum absorption with 99.31 % energy storage capacity and 73.45 % photothermal conversion
Natarajan et al. 2023[91]	HS-01	Hybrid portable solar based cold storage system	1 °C, 350 J/g	Application of PCM reduced the energy consumption by 17.9 %
Shuiab et al. 2023[92]	n-eicosane/carbonized watermelon peel/MnO2 nanosheets	Vacuum impregnation/Solar energy saving and conversion	42.32 °C, 220 J/g	94.5 % high energy storage to conversion efficiency noted with PMC composite

prevent overheating. They improve the thermal management of electronic equipment by releasing the heated energy when needed. High-density data storage in data storage devices is made possible by solid–solid phase change materials (PCMs). They represent binary data by alternating between crystalline and amorphous phases and have quick read/write rates and increased store capacity. The scope of PCM applications for data storage and thermal management is represented in Fig. 9.

By submerging RT 25 PCM-calcium alginate capsules made by microfluidic encapsulation in eutectic gallium-indium liquid metal (LM), Wang et al. created a PCM-LM composite. Significant gains over pin–fin heat-sink cooling were made when this composite was utilized as a CPU heatsink. Due to the composite's superb responsiveness and thermal buffering effect, 23 % less energy was used, and continuous full load operating time could be increased by 414.3 %.

Sreenath et al. examined the effect of PCM and ambient conditions on the thermal performance of a metal foam (MF)-PCM composite heat sink. Three PCMs, i.e., Paraffin wax (PF), docosane (DOC), and eicosane (EIC), were employed to carry out the investigation. According to the study, adding metal foam to the PCM decreased peak temperature by 15.1 % and lengthened the time it took to attain a given temperature by 1.8 times. Additionally, the study discovered that a rising ambient temperature decreased the length of the PCM's latent heat phase and considerably raised the highest temperature that could be reached in the

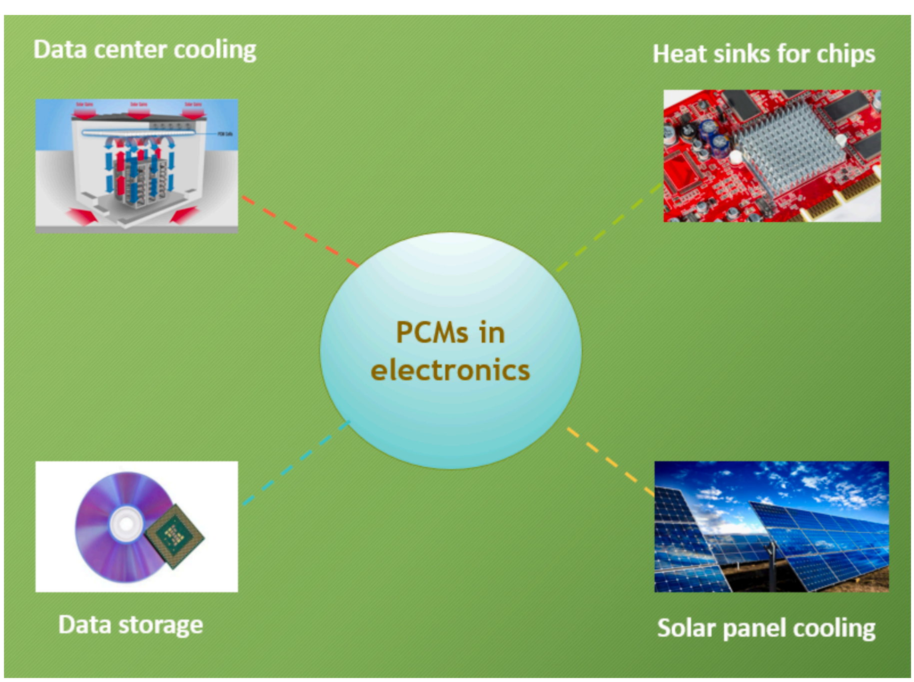

Fig. 9. Schematic of Phase Change Materials (PCMs) for Thermal Management and Data Storage in Electronics.

heat sink. While DOC-MF-Cu performs better under high heat input and higher ambient temperature settings, the study suggests a low melting point PCM-MF composite for normal and intermediate ambient circumstances. Composite heat sinks based on high melting point PCM demonstrated improved charge–discharge cycle readiness at high temperatures.

Carbon nanoparticles (graphene and carbon nanotubes) and PCMs (RT 35, RT 44, RT 54 and paraffin) were used by Bouguila et al. to create a heat sink, which was then optimized utilizing multilevel reliability-based techniques and parametric analyses using MATLAB and ANSYS Finite element models. The Robust Hybrid Method was proven efficient at recommending the best heat sink design using a range of nano-enhanced phase change materials. PCM sink lowered temperature by 25 % (16.5 °C), and shortened discharge duration by 8.69 % (14 min) in comparison to the baseline heat sink.

Liao et al. examined the effects of time ratio, heating power, and cooling water temperature on thermal control and periodic stability while testing a thermal management system based on a No. 28 paraffin PCM for cooling high-power blade servers inside data centers. The findings show that it is occasionally feasible to maintain the heating surface's peak temperature below 80 °C for extended periods. Based on their findings, they suggested a design approach for the system's features and a technique for reducing the number of measurement points.

Kim et al. performed numerical simulations to investigate the effects of a horizontal fin arrangement on the thermal performance of a heat sink containing PCM. The phase transition and air interface of the PCM were studied for six horizontal fin positions using the enthalpy-porosity approach. A fluid volume model was used to keep track of the working fluid inside the heat sink. The storage ratio and time needed to attain the set point temperature (SPT) were recorded for each fin arrangement. The amount of time required to achieve the lowest SPT and maximum storage ratio occurred when horizontal fins were positioned in the center of the heat sink. There was a design for horizontal fins that could efficiently store the thermal energy supplied to the heat sink, and the energy storage rate increased by 3.8 % when horizontal fins were present.

Said et al. studied the effectiveness of PV modules with integrated passive and active mist cooling. Due to their availability, environmental friendliness and stability, paraffin wax was chosen as a PCM and coconut husk as a passive cooling material. The outcomes demonstrated that, compared to the reference PV panel, PCM cooling decreased surface temperatures at the front and back of the PV panel by 0.92 % and 12.83 %, respectively. Husk raised the front and back surfaces' surface temperatures by 2.07 % and 0.33 %, respectively, which reduced PV power by 0.82 %. Hybrid cooling, which mixes active mist cooling and passive cooling, improved the cooling process. As a result, the PV-PCM with mist cooling offers a more effective and affordable heat sink thermal cooling solution than competing techniques.

To create thermally conductive PCM composites, Lee et al. created a unique PCM employing poly(dimethylsiloxane) (PDMS, (bis-hydroxyalkyl) terminated)-grafted palmitic acid (PA) and PDMS grafted expanded graphite filler. These composites have dramatically increased through-plane thermal conductivity, latent heat(106.93 J/g), and tensile stress, which qualifies them for sophisticated applications in PCM composites and complicated electronic packaging.

Hassan et al. studied the use of nano-enriched PCM (NEPCM) in copper foam with a 97 % porosity for passive cooling of electronic equipment. The PCM employed was PT-58; nanoparticles were 0.01 wt % graphene nanoplatelets (GNP) and 0.02 wt% magnesium oxide (MgO) nanoparticles. For various power loads, different combinations of nanoparticles reduced the maximum base temperature by 12.5 % to 16 %. GNP-based copper foam PCM composites took longer to reach the set temperatures than MgO-based composites. They discovered that adding copper foam to NEPCM is a workable way to reduce the heat sink base temperature and offer the optimum cooling performance under low and heavy heating loads.

Song et al. suggested porous SiC ceramics derived from starch to obtain high heat conductivity and inhibit PCM leakage. The use of directional pore designs and thick grains enabled the production of porous SiC ceramics with excellent thermal conductivity (30 W/m-K) and 80 % porosity. SiC was used to make composites with two PCMs, i.e., Paraffin and Li salt eutectic PCM. After 500 repeated heating–cooling cycles, the thermal conductivity and thermal energy storage density (59.23 J/g) of SiC/paraffin composite PCMs (CPCMs) decreased very little, demonstrating their extraordinary stability and durability for application in thermal regulation of high-power electronics. Further, this study reported a composite of SiC with 79 % LiOH-21 % LiF eutectic PCM showing high latent heat storage of 331.56 J/g. The SiC/Paraffin composite, when applied for chip cooling, reduced the maximum temperature of the chip by 10 °C compared to conventional copper.

Arshad et al. created new composite materials by distributing graphene nanoplatelets (GNPs), multiwall carbon nanotubes (MWCNTs), aluminum oxide (Al_2O_3), and copper oxide (CuO) into RT-28HC PCM (melting properties: 28 °C, 254.73 J/g). Using a fixed mass percentage of each kind of nanoparticle, they created mono and hybrid nano-enhanced phase change materials (NePCMs). Without altering the chemical composition of RT-28HC, the results demonstrated that all NePCMs had better chemical and thermal stability. Compared to pure PCM, the hybrid NePCM of GNPs/MWCNTs exhibited the most significant improvement in thermal conductivity (96 %), with a phase-change enthalpy of 245.18 J/g.

The discussion of various literature on the application of PCMs in various electronic units is summarized in Table 6.

Summary

PCMs can cool high-power electronic chips, solar panels, and data centers. When used as heat sinks, thermal conductive PCM composites reduce the peak temperature, increase the time to reach the set point temperature, and reduce energy consumption. The maximum temperature of the heat sink was decreased by 10–16 °C when PCM composites were used in the heat sink, and energy consumption was saved by 23 %. The PCM sink performance depends on both the melting temperature of PCM and ambient conditions. When three different melting PCMs were used in the metal foam PCM composite heat sink, the low-melting PCMs performed better at lower to mid-ambient temperatures. In contrast, the high melting PCM was better for higher ambient temperature conditions. PV cooling using paraffin PCM reduced the front and backside temperatures of PV panels by 0.92 % and 12.83 %. The rice husk increased the panel's temperature, and the hybrid cooling system with combined PCM-Cool mist increased the performance of the PV Panel.

3.6. Power generation

Phase change materials (PCMs) are employed in power generation for effective heat management and energy storage. PCMs are used in concentrated solar power (CSP) plants to store extra thermal energy produced during the day by concentrated sunlight. When there is insufficient sunlight or a strong energy demand, this stored heat is released, powering turbines to produce electricity continually. By controlling the panels' temperature, PCMs improve the power output of solar panels. They store extra heat, keeping solar panels from overheating and preserving their efficiency, which increases energy output. The performance of thermoelectric generators (TEGs), which turn heat into electricity, can be improved with the help of PCMs. TEG temperature changes are controlled by PCMs, which increases the efficiency of PCMs in producing electricity. PCMs control temperature swings to turn waste heat into electricity. PCMs collect extra heat to increase energy efficiency and release it to thermoelectric generators. The application scope of PCMs in various power generation technologies is presented in Fig. 10.

He et al., using their 3-D model, identified three issues that lower the efficiency of hybrid power generation systems that use phase change temperature control and radiation heat sink technology under space

Table 6
Literature Review: PCM Applications in Thermal Management of Electronics.

Author	PCM/shell	Method/application	Properties	Remarks
Wang et al. 2023[93]	Rubitherm RT 25/ calcium alginate/ Gallium-indium liquid metal eutectic mixture	Microfluidic encapsulation/ data center cooling	25 °C,8.14 J/g	Microencapsulated PCM-liquid metal composite showed a 23 % reduction in energy consumption
Sreenath et al. 2023 [94]	paraffin wax, docosane and eicosane PCMs/ metal foam copper and aluminum composites	Heat sink for electronics cooling	Paraffin wax-44.5–60.1 °C, 148.93 J/g, docosane-40.3–44.5 °C,263.46 J/g eicosane- 36.3–38.1 °C, 252.06 J/g	Different metal foam PCM composites were shown to have better performance for various ambient conditions
Bouguila et al. 2023 [95]	RT 35, RT 44, RT 54 and Paraffin/ carbon nanotubes (CNT) or graphene (GNP)	Heat sink for electronics cooling	RT 35—32 °C, 160 J/g, RT 44—41 °C, 239 J/g, RT 54—53C, 221.5 J/g and Paraffin-58C, 235.65 J/g	The PCM heat sink reduced the maximum temperature by 16 °C and discharge time decreased by 8.69 % compared to the reference sink
Liao et al. 2023[96]	No. 28 paraffin wax inside tube fin cool storage heat exchanger	Thermal management system for heat dissipation of blade servers in data centers	28 °C, 200 J/g	The peak temperature of the heating surface was maintained below 80 °C using PCM thermal management system
Kim et al. 2023[97]	RT 27	Heat sink with horizontal fins for electronics cooling	30 °C, 175 J/g	Heat sink with PCM took 3.31 times more time to reach the set point
Said et al. 2023[98]	Paraffin wax	PV module cooling with different setups PCM, husk and mist	56–60 °C	Incorporation PCM decreased the operating temperature of PV module and increased the energy generation
Lee et al. 2022[99]	Palmitic acid/expanded graphite	PCMs based composites for advanced electronic packaging and cooling	60–62.5 °C,106.93 J/g	The composite prepared with polydimethyl siloxane(PDMS) grafting in PCM and expanded graphite had high thermal conductivity and tensile stress
Hassan et al. 2022 [100]	PT-58/ graphene nanoplatelets/ magnesium oxide nanoparticles/ copper foam	Heat sink for electronic chip set cooling	58–60 °C, 225 J/g	NEPCM/copper composite showed better performance than PCM or NEPCM heat sink
Song et al. 2022 [101]	Lithium hydroxide-lithium fluoride (79:21) eutectic PCM or paraffin/porous starch derived SiC ceramics	Thermal management of high-power electronics	LiOH-LiF eutectic PCM- 428.04 °C, 331.56 J/g Paraffin- 45–55 °C, 59.23 J/g	Temperature of high-power chip reduced by 10 °C using SiC/paraffin composite than normal copper
Arshad et al. 2020 [102]	RT-28HC with graphene nanoplatelets(GNP) / multiwall carbon nanotubes (MWCNT) / copper oxide/aluminum oxide nano particles	Thermal management of micro electronics	27–29 °C, 245.18 J/g	Hybrid nano PCM with GNP/MWCNT (75 %/25 %) showed 96 % improvement in thermal conductivity compared to pure PCM and had enthalpy of 245.18 J/g

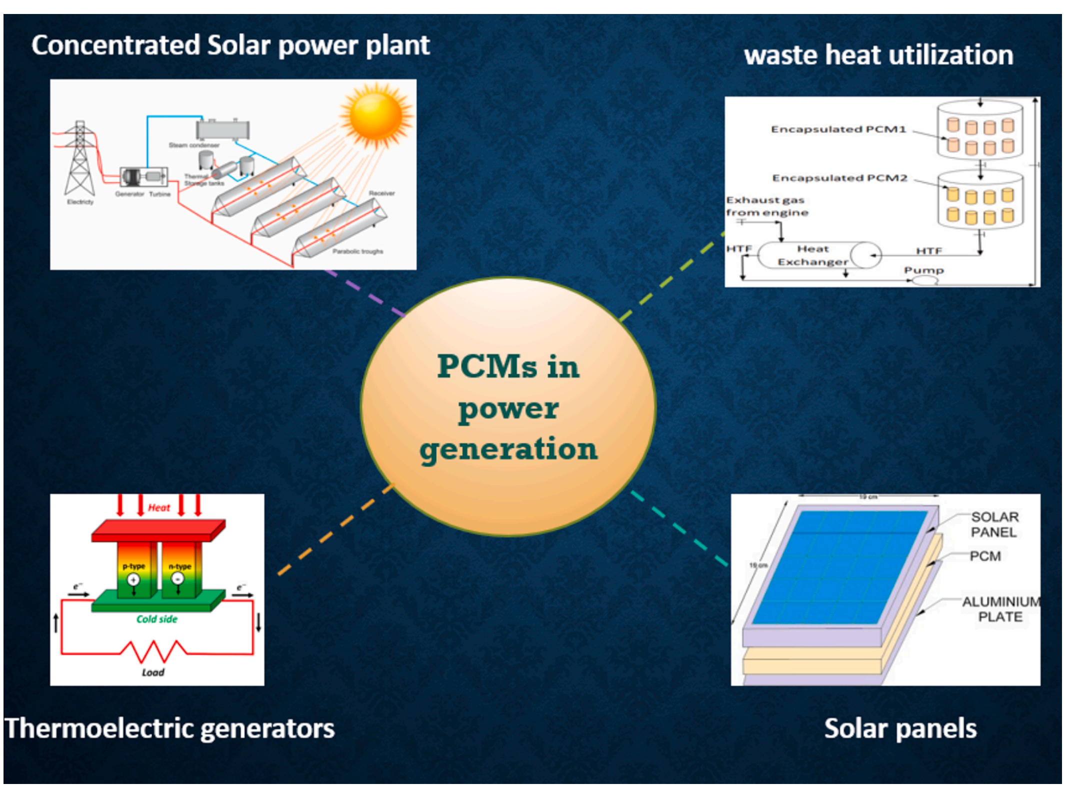

Fig. 10. Schematic of Phase Change Materials (PCMs) for Enhanced Power Generation.

circumstances. Then, to increase system efficiency, they developed a heat transfer pillar for the temperature control unit and circular heat sink fins for the heat sink. The optimized structure hybrid system's electrical efficiency and power density were balanced, and the interaction was then resolved using a multi-objective evolutionary algorithm and artificial neural network. The system with PCM thickness PCM = 6.33 mm, heat transfer pillar width a = 18.19 mm, fin length L = 49.99 mm, and fin radius R = 50 mm had the highest average overall efficiency (31.83 %). System with dPCM = 3.02 mm, a = 10.05 mm, L = 47.03 mm, and R = 25.86 mm showed greatest average power density (36.97 W/kg).

Win et al. performed an experimental analysis of the thermal properties and power generation of TEG façades under various solar heating circumstances. The findings revealed that the maximal power output for TEGs attached to a typical structural façade employing a 25 cm-thick reinforced concrete (RC) was 100.0 mW/m^2. The TEG coupled to the 2.5 cm thick microencapsulated phase change material (mPCM) honeycomb board had the highest energy ratio for TEG non-structural façades when it came to internal heat gain.

Rejeb et al. looked at the effect of PCM on combined solar photovoltaics with thermoelectric modules (CPV-TEG) system performance for two different climatic zones (Mediterranean and hot desert climate zone). PCM could be simultaneously used to cool the PV and cold sides of the thermoelectric modules, thereby helping boost the power output. The study assessed the power output, temperature fluctuations, and conversion efficiency of a CPVT-TE collector with an RT 26 PCM. The results demonstrate that rising solar radiation increases CPV and TEG module electrical output as it helps completely melt PCM. The highest electrical outputs recorded in Dubai conditions for CPV and TE modules were 170 W/m^2 and 1.317 W than Napoli conditions (66 W/m^2 and 0.127 W) on summer days.

The solar thermoelectric wall utilizing phase change material (STEW-PCM) was created by Hong et al. as a means of power production designed explicitly for subtropical conditions. The system has promising capabilities for continuous power generation, boasting an annual electrical energy output of 1740.66 kJ/(m^2·year). It also demonstrated a levelized electricity cost of 35.37c\$/kJ and a CO_2 saving cost of 6.74 \$/(m^2·year). The cooling load could be reduced by more than 25 % using a PCM wall in subtropical climate conditions.

Zeng et al. developed double-shell salt PCM (Na_2CO_3: Li_2CO_3 57:43 wt%) macrospheres with an inside expanded graphite (EG) layer and an exterior ceramic kaolin layer. The double shell-coated macrocapsules for prolonged use showed extraordinary stability and remarkable durability. The eutectic core PCM had a melting temperature of around 498 °C and a latent heat of 313 J/g. Further, the macrocapsules were found to have a heat storage capability of 380 J/g in 400–600 °C temperature range. These macro encapsulated PCM capsules could be used for high-temperature heat storage applications in solar thermal power plants and industrial waste heat recovery.

Alavy et al. created a thermal caisson (TC) system based on phase change material (PCM) for geothermal cooling and heating through ground heat exchanger U-tubes. They used an algorithm for the long-term energy performance evaluation of the ground source heat pump (GSHP) systems. According to the study, using a PCM may dramatically raise the long-term COP of GSHP by 22 % and improve the energy performance of TCs. PCM-embedded GSHP system had a 65 % higher return on investment and 19 % lower CO_2 emission in long-term use for 20 years compared to the conventional GSHP system.

Joung et al. created a thermoelectric generator-assisted energy harvesting block containing PCM and a thermal electric generator to use the waste heat from external building walls. They explored the effect of different electrical configurations of energy-collecting blocks on the exterior resistance. Experiments were carried out for nine cases by connecting 1.6 Ω, 15 Ω, and 60 Ω with the same internal resistance as the external resistance of the array. The current and voltage were more affected by connected external resistance than the array type. The maximum generated energy was 0.837 Wh/day with 60 Ω connected to a series arrangement and based on the sol–air temperature profile in December.

To increase the efficiency of solar panels in terms of power output and thermal utilization, Hamada et al. suggested a novel water-based PVT system combined with RT 35 PCM capsules (PVT-PCM panel). According to the findings of experiments conducted in various actual outdoor climatic conditions of Cairo, Egypt, the actively cooled PVT-PCM panel exhibited the highest electrical and thermal energy gain at 3 L/min cooling water flow rate, resulting in a maximum cumulative total efficiency of 74.1 %. The cumulative efficiencies of reference and passively cooled PV panels were 12 % and 34.6 %.

By creating a computational fluid dynamics (CFD) 3D model to conduct numerical research of heat transmission, Jurcevic et al. investigated the robust performance of the one-of-a-kind free-standing photovoltaic-thermal (PVT) collector with pork fat as an integrated phase change material (PCM) under a variety of weather conditions. The comparison with experimental data effectively verified the numerical model. The observed mean absolute percentage discrepancy between the numerical forecast of the operating temperature and the experimental data ranged from around 2.9 % to 4.9 %, with variations depending on the specific area under consideration. The findings may be applied to boost the resilience component early in the creation of innovative designs, examine the effects of various operational parameters on system performance, and upgrade the current PVT-PCM collector designs.

The Rotating Drum Heat Exchanger was proposed by Tombrink et al. as a thermal energy storage device for enhanced co-generation of electricity and carbon–neutral steam generation. At steam pressures of 2.5 bar, 8 bar, 20 bar, and 75 bar, the storage system is capable of producing 20,000 kg/h of saturated steam, which translates to a surface-specific heat transfer of more than 300 kW/m^2 and an electricity output of up to 24 %. The summary of various literature reports on power generation is provided in Table 7.

Summary

PCMs help generate electricity through concentrated solar power plants, thermoelectric generators and solar panels. Studies revealed that a 2.5 cm thick microencapsulated PCM honeycomb board attached to 25 cm thick reinforced concrete as a façade could generate the maximum electrical output of 100 mW/m2. A solar thermoelectric wall utilizing PCM was found to reduce carbon emission costs of 6.74 \$/m2 with an annual electric energy output of 1760.44 kJ/m2.year. The melting of PCM for application in solar thermal walls was optimum in the 40–50 °C range. Further, applying phase change materials in cooling solar panels, thermoelectric generators, and thermal caisson geothermal systems helps improve electricity output. A study revealed that the PVT-PCM panel and 3 L/min water cooling rate showed a cumulative efficiency of 74.1 %. PCM application in concentrated photovoltaic thermal electric systems increased the power generation efficiency and storage density by 2.98 % and 15.78 %. High-temperature melting PCMs like eutectic of sodium carbonate/lithium carbonate PCM (498 °C), sodium nitrate (306C) and eutectic of sodium nitrate/ potassium nitrate (222 °C) are mainly used in concentrated solar power plants for storing thermal energy thereby generate electricity through steam generation. Applying high-temperature melting PCMs like sodium nitrate and eutectic of sodium and potassium nitrate in a rotating drum heat exchanger increased the volumetric storage density by 53 %-65 %, ultimately increasing the power generation by 24 %. A wide variety of PCMs could be used for power generation applications with PCMs in melting range of 20–50 °C for solar panel cooling and thermoelectric generators, while high melting PCMs above 200 °C are used in concentrated solar power plants.

Table 7
Summary of Strategies for Utilizing PCMs in Power Generation:

Author	PCM/shell	Method/application	Properties	Remarks
He et al. 2023 [103]	Paraffin wax	PCM based concentrated photovoltaic thermoelectric system for space	43–46 °C, 255 J/g	Power generation efficiency and power density were improved by 2.98 % and 15.78 %
Win et al. 2023 [104]	Paraffin micro encapsulated capsules	Thermo electric generators facades in buildings	37 °C, 166.54 J/g	Thermo electric generator attached with PCM honey comb board showed highest energy ratio
Rejeb et al. 2023[105]	RT26 paraffin	Concentric photovoltaic system integrated with thermoelectric generator	26 °C, 180 J/g	The highest electric power output from the photovoltaics and thermo electric generator were 170 W/m2 and 1.317 W in Dubai
Hong et al. 2023[106]	PCM with various melting temperatures	Solar thermoelectric wall	Various melting temperatures 30 °C, 40 °C, 50 °C, 60 °C, 70 °C, latent heat 170 J/g	The PCM melting temperature should be in range of 40 °C-50 °C for the designed system
Zeng et al. 2023[107]	Carbonate eutectic salt/ expanded graphite/kaolin shell	High temperature melting PCM for Solar thermal power plant	498 °C, 313 J/g	Na_2CO_3/Li_2CO_3 mixture forms eutectic at 57:43 wt%.
Alavy et al. 2023[108]	RT2HC	Thermal caisson geothermal systems	1–3 °C, 200 J/g	PCMs found to greatly influence the performance of thermal caissons
Joung et al. 2023[109]	Microencapsulated PCM capsules	Thermoelectric energy harvesting blocks in buildings	28 °C, 145 J/g	Voltage and current were more effected by connected resistance than type of array
Hamada et al. 2023[110]	Rubitherm 35(RT35) paraffin wax/ copper balls	Photo voltaic thermal collector	35 °C, 160 J/g	Actively cooled PCM-PVT system had 74.1 % cumulative efficiency compared to 12 % for reference
Jurcevik et al. 2023[111]	Pork fat	Photo voltaic thermal collector	8.3 °C- 45.2 °C, 45.4 J/g	Numerical model of PVT-PCM collector was developed and validated
Tombrink et al. 2022[112]	Sodium nitrate, Sodium nitrate-potassium nitrate eutectic PCM	Designing of rotating drum heat exchanger for electricity generation based on PCM	NaNO3- 306 °C, 178 J/g NaNO3-KNO3 eutectic PCM- 222 °C, 107 J/g	Volumetric storage density of tank increased by 65 % and 53 % using NaNO3 and eutectic PCM

3.7. Food and beverages

Temperature-sensitive foods and beverages must be stored and transported using phase change materials (PCMs). To guarantee that products keep the proper temperature throughout the supply chain, PCMs are integrated into packaging materials, refrigeration systems, and thermal blankets in these applications. Thermally sensitive foods are mainly confectionaries, vegetables, fruits, dairy products, ice creams, etc. Different thermosensitive foods that require PCMs during transport and storage to avoid thermal fluctuations are shown in Fig. 11.

Rahimi-Khoigani et al. designed and verified computational models for investigating the influence of heat sinks on the phase change material (PCM) melting process within latent heat storage systems (LHSS). Two systems were created, one referred to as LHSSB, which does not include a heat sink, and the other referred to as LHSSI, which incorporates a heat sink. The study's findings indicate that applying LHSSI enhanced temperature stability, leading to a significant reduction of 84 % in mushroom browning during a storage period of 4 days. Additionally, the LHSSI treatment was shown to reduce the melting time of PCM by 700 s.

In their study, Nabi et al. successfully encapsulated tetradecane within a calcium alginate shell, attaining the most extraordinary efficiency. Various characterization methods were employed to analyze the capsules. The alginate films containing 5 % sodium alginate and 12 % calcium chloride exhibited the lowest level of leakage and demonstrated

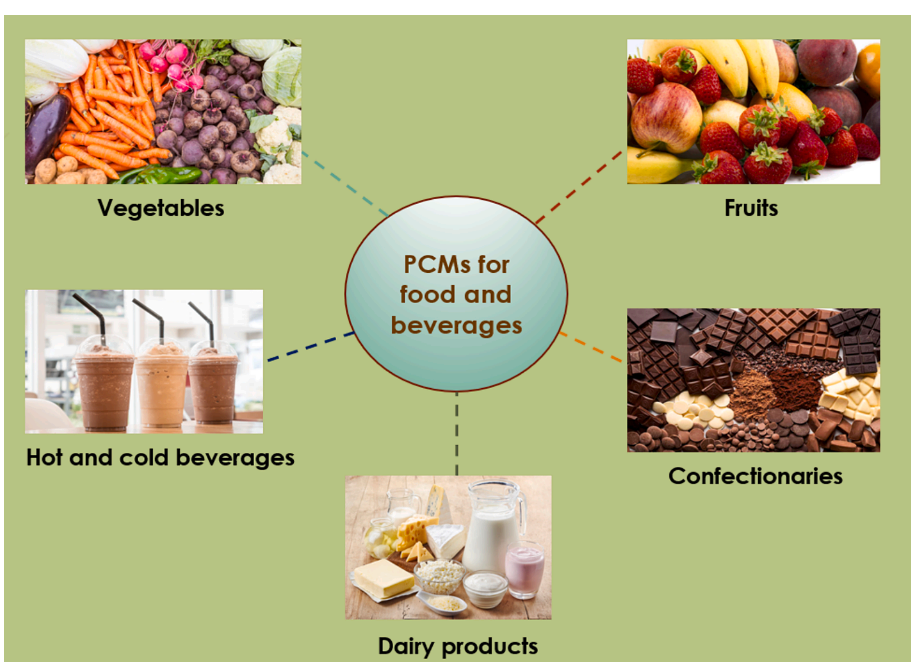

Fig. 11. PCMs Ensuring Safe Temperatures for Thermosensitive Foods during transportation and storage.

superior structural integration. The inclusion of PCM (Phase Change Material)-incorporated packaging delayed the increase of meat temperature, resulting in reduced weight loss and increased levels of hardness, gumminess, and chewiness.

To create a novel form-stable cold energy storage phase change material (FCPCM), Zhang et al. used ice as the phase change component and a three-dimensional network made of polyether as the skeleton, which could maintain temperatures cold 1.8 times longer than normal ice. FCPCMs showed good thermal characteristics, negligible water leakage, and excellent form stability.

Liu et al. created a cold energy storage material 6-PCM5 with good static and cyclic stability using an organic water-based PCM with high latent heat and a melting temperature of −4°C to −6°C. Glycine, mannitol, and potassium sorbate were used to create 6-PCM5, which had a reasonable melting temperature and moderate thermal conductivity. The basic PCM was an aqueous solution of glycine and mannitol, modified with 0.1 wt% potassium sorbate to increase static stability. The melting temperature decreased by 2.24 % after 100 thermal cycles. It was found that 6-PCM5 had a cold storage period of 22.83 h and a lower average temperature for strawberries than ice as a PCM.

Qin et al. produced composite phase change materials (PCMs), including 1-decanol, expanded graphite, and silica aerogel. The optimal concentrations of EG and SA were 9 and 14 wt%, respectively. The composite phase change materials (PCMs) exhibited favorable thermal stability after undergoing 220 heating and cooling cycles. In addition, these composites successfully upheld yogurt's desired temperature and acidity levels without a cooling system, rendering them appropriate for transporting temperature-sensitive items within the cold chain.

To control chocolates' temperature, stability, and physical form, Singh et al. created innovative Ba-alginate shell-based encapsulated PCM beads. Encapsulation helped with increasing surface area, albeit at the expense of enthalpy. PCM capsules with a maximum enthalpy of 149.15 J/g were coated with polyurea to improve thermal stability. However, the increased content of the polyurea shell resulted in an enthalpy decrease to 76.7 J/g. 60 g of polyurea-coated alginate PCM beads could maintain the temperature of 240 g chocolate for 86.28 min under 25 °C inside a temperature-controlled packaging(TCP) box.

In their study, Reddy et al. employed a blending-ultrasonication technique to produce a eutectic PCM OD-64 by combining OM-21 with 1-dodecanol. This research aimed to explore the potential application of OD-64 in the temperature management of chocolates for their storage and transportation processes. The eutectic composition of PCM exhibited distinctiveness, as evidenced by a single crystallization peak at 0.68 °C, lower than that of any PCM used for preparation. The time required for charging and discharging a 180 g PCM within a TCP box was determined as 65 and 48 min, respectively. The intended TCP box provided a thermal buffering of 390 min for 240 g of chocolate at ambient temperature. The software tool COMSOL Multiphysics 5.5 is used to create a three-dimensional TCP box model. Subsequently, the model equation was subjected to validation through experimentation conducted at various ambient temperatures.

In order to address the thermal buffering use in food packaging, Parvate et al. created a unique type of functionalized copper nanoparticles (CuNPs) interconnected polydivinylbenzene (PDVB) microcapsules utilizing hexadecane as phase change material (PCM). Transmission electron microscopy (TEM) and Fourier transform infrared spectroscopy (FT-IR) characterizations proved that CuNPs were successfully functionalized and present in the PDVB shell. Results from scanning electron microscopy (SEM) showed that the generated microcapsules had a spherical shape and a well-defined core–shell microstructure. Microcapsules with 1 % CuNPs had an encapsulation ratio of 60.5 % with a maximum enthalpy of 132 J/g. Thermal buffering experiments showed that 30 g of PCM capsules provided thermal buffering of 6.5 h for 240 g of chocolate to keep temperature between 5–35 °C.

Vennapusa et al. explored the problem of keeping a steady milk temperature for curd formation in cold ambient conditions using lauric acid as a phase change material (PCM). A TCP box was designed with 240 g of PCM evenly dispersed within six polyethylene packets (40 g each) with dimensions matching those of the inner walls of the corrugated box. It was observed that 150 g of milk (put within the TCP box) could be kept at a temperature between 50 °C and 30 °C for 160 min using 240 g of melted PCM, which aided in curd formation.

Stable phase change material (PCM) composites were produced by Reddy et al. employing OM-11 in three support matrices, i.e., activated charcoal (AC), silica-gel, and rice husk. Rice husk composite performed poorly; silica composite had lower phase change performance than activated charcoal composite. The PCM-AC composite eliminated energy storage problems and supercooling behavior. In the TCP box test, 700 g PCM-AC composite was utilized to keep tomato temperatures below 14 °C for 510 min and 250 min when ambient temperatures were 23 °C and 43 °C.

The summary of various literature research reports on application of PCMs for transport and storage of various thermal sensitive foods is given in Table 8.

Summary

During storage and transportation, PCMs are mainly used to maintain the temperature of thermal-sensitive food materials like fruits, vegetables, chocolates, etc. Low-temperature melting phase change materials with melting temperatures between −10 °C and 25 °C are used for thermal buffering applications. PCMs with a melting temperature range of 2–8 °C are very useful for storing and transporting thermal-sensitive food. PCMs with macro/micro/nano encapsulations could provide thermal buffering. The PCMs can maintain the temperature of products from minutes to days depending on the quantity of PCM and thermal properties of PCM. One study showed that the temperature of 240 g chocolate can be maintained for 6.5 hr using 60 g micro-encapsulated hexadecane capsules. Further, studies showed that the quality of foods like mushrooms, litchi, meat, strawberries, chocolates, tomatoes, etc could be preserved using PCMs. Interestingly, PCM lauric acid was used to design a box to aid in the formation of curd in cold ambient conditions. The melting phase change of PCM can provide thermal buffering when the product temperature has to be kept at lower temperatures than the ambient temperature and vice versa; solidification phase change was used when the product temperature has to be kept higher than the ambient temperature.

3.8. Water treatment

PCMs can be used in water treatment applications to improve the energy efficiency of solar stills for saltwater desalination. PCMs are fitted to store extra heat during evaporation and condensation in thermal desalination processes. When energy demand is high or during off-peak hours, the heat stored in the system is released, creating a steady heat source for desalination. This load-shifting ability lowers energy costs, guarantees continuous freshwater production, and lessens the adverse environmental effects of the desalination process. Different types of solar stills are shown in Fig. 12. By maximizing energy use, PCMs help increase solar still overall sustainability, making them more economical and environmentally benign, especially in areas where water scarcity and energy issues are prevalent. The phase change microcapsules containing nanoparticles could also be used to degrade pollutants in industrial waste wasters.

Tiwari et al. explored the effect of positioning the PCM composite on the performance of solar still by conducting experiments with the conventional solar still (CSS), the CSS with PCM (OM 37) composite in copper pipes, and the CSS with PCM composite under the basin liner and separated by copper sheet. The findings imply that solar still constructed of PCM composite under basin performed better than others.

Using paraffin wax PCM, Rousta et al. conducted an experimental investigation to improve the functionality of a tubular solar still. They looked at three approaches: pure PCM, PCM boosted with Co_3O_4, and

Table 8
Summary of Research on Phase Change Material (PCM) Applications for Thermal Management of Food and Beverages

Author	PCM/shell	Method/application	Properties	Remarks
Rahimi-Khoigani et al. 2023 [113]	Tetradecane	Food packaging of mushroom and tylose (MH 1000)	6.72 °C, 206.3 J/g	PCM package with fins showed better performance than without fins
Nabi et al. 2023 [114]	Tetradecane/calcium alginate	PCM incorporated film for thermal regulation of meat	5 °C, 223.51 J/g	5% sodium alginate and 12% $CaCl_2$ film composition PCM film preserved meat quality for long time
Zhang et al. 2023 [115]	Ice/polyether based three-dimensional matrix	Cold chain logistics to preserve litchi fruits	1.9 °C, 285.9 J/g	Form stable PCM composite maintained temperature 1.85 times longer than pure ice
Liu et al. 2023 [116]	6-PCM5(Glycine and mannitol water-based solution)	Precooling and transportation of straw berries	-5.78 °C, 292.64 J/g	Precooling time of strawberries using 6-PCM5 was reduced by 68.4% compared to ice
Qin et al. 2023 [117]	1-decanol/ expanded graphite (EG) and silica aerogel (SA)	Yogurt preservation	EG-PCM: 3.32 °C, 188.31 J/gSA-PCM: 4.1 °C, 160.81 J/g	Composites of PCM with EG and SA held the temperature of yogurt in 2-8 °C for 7.9 h and 8.9 h
Singh et al. 2022 [118]	1-dodecanol/alginate-polyurea	Ionotropic gelation-dip coating/ Design of temperature control packaging box for chocolates	22.05 °C, 76.67 J/g	60g PCM alginate urea beads delayed heat transport by 86.28 min for 240g chocolate
Reddy et al. 2021 [119]	OD-64(eutectic of OM-21 and dodecanol)	Thermal regulating packaging box	7.38 °C and 12.21 °C, 140.6 J/g	180g PCM provided 390 min thermal insulation time for 240g chocolate
Parvate et al. 2021 [120]	Micro capsules of Hexadecane/polydivinyl benzene-copper nanoparticles	Suspension polymerization/ thermal regulating package for chocolates transportation and storage	17.8 °C, 132 J/g	Temperature of 240g chocolate was maintained in the range 5-35 °C using for more than 6.5 h using 60 g microPCM capsules
Vennapusa et al. 2021 [121]	Lauric acid	Temperature regulation of milk for curd formation	45.02 °C, 189.43 J/g	240g PCM kept 150g milk temperature for 160 min over 30-50 °C
Reddy et al. 2020 [122]	OM-11/ activated charcoal (AC) or silica gel (SG) composites	Direct impregnation/Thermal regulation of tomatoes for storage and transportation	PCM-AC composite- 9.6 °C, 69.24 J/g, PCM-SG composite- 9.54 °C, 52.65 J/g	Activated charcoal PCM composite performed better than silica gel PCM composite

PCM augmented with aluminum shreds. The thermal characteristics of paraffin wax were enhanced by copper tubes containing scrap metal from industry and baffles painted with micro Al_2O_3-black paint, improving solar still production and efficiency. In terms of the overall output, the three setups surpassed the standard solar still with a cuboid basin by 5.69 %, 15.30 %, and 24.56 %, respectively.

By making numerous adjustments, Sharshir et al. enhanced the thermo-enviroeconomic properties of a hemispherical solar still (HSS). The solar still performance was explored by employing four different arrangements, i.e., corrugated copper covered with black cotton fabric as the absorber and paraffin as PCM, filled under the absorber. The second is the same setup, replacing paraffin with sheep fat as PCM; the third is graphite nanofluid, used in the basin; and the fourth is replacing pure sheep fat with graphite-enhanced sheep fat. The daily yield augmentation ratios for four cases were improved by 43 %, 59.77 %, 78.77 % and 95.2 %. The final setup in the study showed better performance than other cases. Thermal and exergy efficiencies in the final example were 61.7 % and 5.8 %, respectively and as a consequence, expenses were cut by 33.90 %, while CO_2 emissions dropped by 6.27 tons per year.

Sathyamurthy studied the Ag nanoparticle-based stepped basin solar still (SS) with paraffin wax (PW) and evaluated its thermal performance and palatable water production with and without PW. The findings revealed that compared to the SS with thermal energy storage and the SS without thermal energy storage, the annual output of palatable water from the SS with the Ag-doped PCM was increased by around 18.42 % and 120.72 %, respectively.

Using COMSOL software, Mustafa et al. carried out a numerical analysis on a transient solar still (SOST). They employed a PCM layer, aluminium nanoparticles, and other factors to model the desalination process. The study discovered that temperature, volume fraction, moisture, and average moisture concentration increased from morning to noon, and from midday to evening, they dropped. Glass angle lowered PCM temperature. At the same time, PCM thickness reduced PCM volume fraction in desalination water by 35 %.

The double slope solar still (DSSS) with PCM-TES was suggested by Afolabi et al., who used vacuum mold-filling techniques to microencapsulate the PCM-TES in epoxy resin composite. The findings demonstrated that DSSS-TES generated 7.5 L more potable water per day and an extension of the operation time by three hours. Adding TES to the system decreased heat losses and stopped PCM nanocomposite leaks.

Modified solar stills (MSS) and conventional stills (CSS) were the subjects of an experimental investigation by Abdullah et al. They tested MSS utilizing nano-phase change material, internal reflectors, and spiral copper water heating coils. The productivity and thermal efficiency for MSS, MSS-IR, and MSS-IR-PCM were significantly increased. The MSS's distillate output rose by 81 % compared to the CSS by installing an internal reflector to the rear wall. Overall productivity for MSS-IR-PCM was 115 % higher than for CSS while utilizing PCM boosted MSS-IR productivity by 34 %. The cost of distilled freshwater for CSS and MSS-IR-PCM was determined by economic analysis to be 0.03 and 0.0235 $/L, respectively.

Kumar et al. investigated two distinct categories of solar stills, namely conventional sun stills and advanced solar stills (ASS). The use of a nano-scale phase change material, ZnO-PCM, is employed to augment the yield of ASS. The research demonstrated that ASS-ZnO-PCM exhibited the highest thermal efficiency and enhanced yield, reaching values of 51 % and 6600 ml/m^2, respectively. This approach led to a significant enhancement in cumulative yield, with an approximate rise of 113 % compared to the usual SS method. Consequently, there was a notable boost in productivity, amounting to a 36 % gain.

To examine a novel design for single distillers (SS), Ellappan et al. conducted tests employing Paraffin wax-phase transition materials (P). They used Ag nanoparticles (A) in Ricinus Communis (RC) leaf extracts to test and validate the designs and decide which outperformed the others under challenging environments. The productivity increase and thermal efficiency were, respectively, 28.5 %/38.3 % (PRC), 66 %/44 % (ARC), and 96.5 %/48.5 % (PARC). The average new SS productivity rise/thermal efficiency for PARC with basin area was 124.2 %/52 %.

After a one-pot non-Pickering emulsion templated suspension polymerization, Paravate et al. created phase change material (PCM)-encapsulating titanium dioxide (TiO_2) nanoparticle decorated poly(4-methylstyrene-co-divinylbenzene) microcapsules. The final

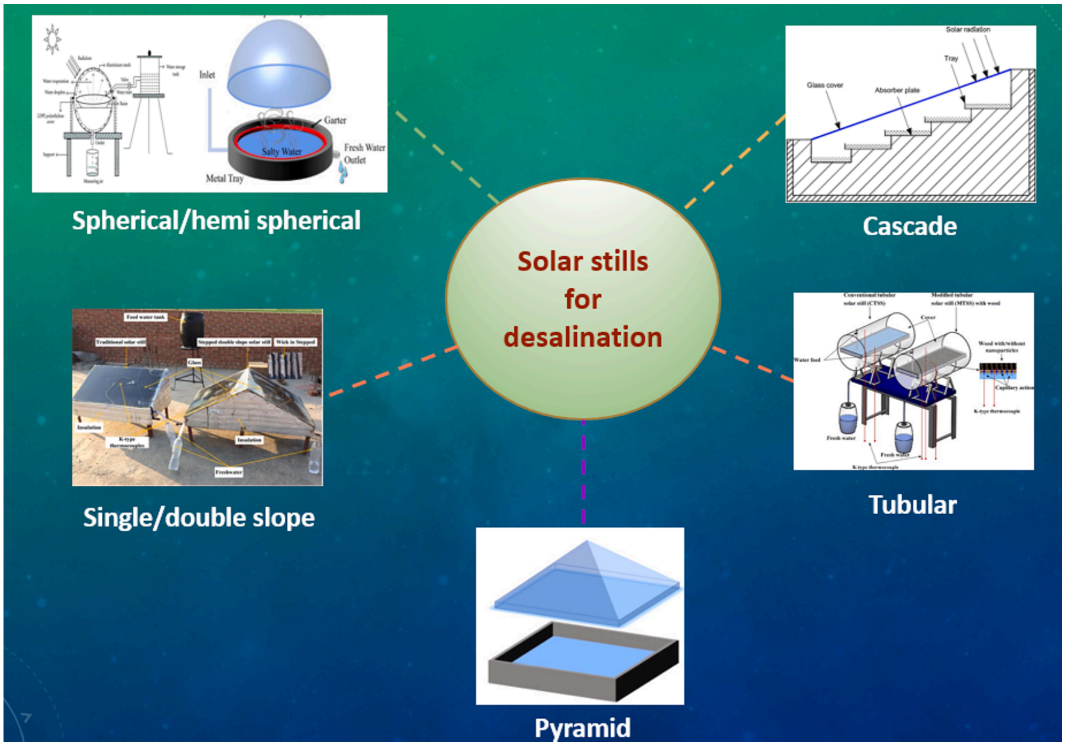

Fig. 12. Pictograph Illustrating Different Types of Solar Stills for Water Treatment (Desalination).

microcapsules showed simultaneous photocatalytic and thermal energy storage capability. These dual-purpose microcapsules can be applied in various fields as depollution agents and thermal energy storage devices. The discussion of literature reports on different applications of PCMs for water treatment is given in Table 9.

Summary

PCMs in water treatment applications are mainly used to produce clean water from salt water using solar stills and degrade water pollutants using multifunctional nanoparticle decorated PCM microcapsules. PCMs enhance solar stills' performance by providing thermal energy even in the absence of sunlight. The position of PCM, nanoparticle addition into PCMs, and thermal properties of PCM will mainly affect the performance of solar stills and enhance water production. Studies showed that employing only PCM or nano PCMs could improve the productivity of stills in the range of 24.56 % to 124 %. Moreover, the employment of PCM increases the working hours of solar stills. Further, the nanoparticles decorated microcapsules of PCM can also be used for photocatalytic degradation of pollutants in water.

3.9. Textiles

Phase Change Materials (PCMs) are widely used in textiles to improve performance and increase thermal comfort in various clothing and fabric items. In reaction to variations in temperature, PCMs that are microencapsulated within textiles can absorb, store, and release heat. Personal apparel is made with PCM-enhanced materials to control body temperature. They create a cozy and reliable microclimate around the body by absorbing extra heat when it's hot and releasing it when it's - cold. The thermal microclimate created by PCM-infused bedding and furnishings prevents overheating and uncomfortable indoor temperatures. To preserve patient comfort throughout medical procedures and recovery, PCMs are used in medical fabrics, including surgical gowns and beds. Various textile-based materials that embed PCM materials are shown in the Fig. 13.

Kumar et al. developed a thermoregulating smart textile by chemically grafting carboxyl-terminated PEG onto cotton, which was then coated with graphene oxide (GO) nanosheets to improve thermal conductivity and UV protection. The cotton textiles had melting temperatures of 58 °C and enthalpy of 37 J/g.

Majd et al. focused on using microencapsulated phase change material Inertek 26P(MPCM) in bio-based textiles to improve energy performance in building envelopes. During DSC test, MPCMs had a melting point at 25.25 °C and phase change enthalpy of 194.9 J/g. An acrylic binder was used to bind the MPCMs to textiles. They developed three types of bio-based textiles i.e.: Biofib insulation with a mixture of hemp/cotton/linen fibers, Biofib insulation with hemp fiber, and Biofib insulation with recycled cotton, including PCM microcapsules. Recycled cotton textiles had the lowest cost per sample and the lowest CO_2 emission rate.

Kong et al. created structural colored textiles with exceptional color visibility and stability for intelligent thermoregulating performance. They used polysulfide microspheres to create amorphous photonic structures (APSs) with high color visibility. Four types of structural colors, purple, green, orange and red, could be obtained using sizes of polysulfide microcapsules comprising 185, 198, 211 and 230 nm. Waterborne polyurethane phase change material (WPUPCM) was used as an adhesive to maintain the structural stability between APSs and textiles with phase change properties of 37 °C and 74.7 J/g. The textiles began to regulate body temperature near the phase change temperature, providing practical options for personal thermal management.

Song et al. produced composite phase change fibers (CPCF), magnetic composite phase change fibers (MCPCF), and crosslinked CPCF and MCPCF textiles using eco-friendly coaxial electrospinning technology. Fe_3O_4 nanoparticles were used as a functional filler to enhance the electromagnetic shielding performance of these fabrics. 20 wt% addition of Fe_3O_4 nanoparticles introduced 9.5 emu/g saturation magnetization, showing 3 dB electromagnetic shielding performance. CPCF and MCPCF had 78.02 % and 69.11 % encapsulation ratios with enthalpies 106.96 J/g and 94.75 J/g. Crosslinking enhanced the fibers' mechanical properties, indicating potential for heat regulation and electromagnetic shielding applications.

Table 9
Summary of Research on Phase Change Material (PCM) Applications in Water Treatment Processes.

Author	PCM/shell	Method/application	Properties	Remarks
Tiwari et al. 2023 [123]	OM 37/ graphite powder	Performance enhancement of solar still for desalination of water	–-	Solar still with composite under basin showed best performance
Rousta et al. 2023 [124]	Paraffin wax/nano Co3O4/Al shavings	Desalination perform enhancement of solar still	44 °C, 190 J/g	Water production increased by 24.56 % using nano PCM/Al
Sharshir et al. 2023 [125]	Paraffin wax and sheep fat PCMs/ graphite nano particles	Performance augmentation of solar desalination unit	–-	95.2 % daily yield augmentation is recorded
Sathyamurthy 2023[126]	Paraffin wax-silver nano particles	Stepped solar desalination still	PW-1 %Ag NP- 57.3 °C, 185 J/g PW-2 %Ag NP- 58.4 °C, 175 J/g	54.67 % more palatable water generated with PCM than without PCM
Mustafa et al. 2023 [127]	n-eicosane	Solar desalination still	29 °C, 241 J/g	Increase in PCM thickness enhanced the PCM and moisture temperature
Afolabi et al. 2023 [128]	Paraffin PCM/Zn nano particles/epoxy mold	Double slope solar still	36–42 °C, –	TES enabled still produced 7.5 L water and had 3 h longer operation than normal still
Abdullah et al. 2023[129]	Paraffin wax-Ag nano particles	Modified solar still	–-	Nano PCM embedded bed showed 115 % improvement in productivity compared with reference
Kumar et al. 2023 [130]	Paraffin wax-ZnO nanoparticles	Solar still	–-	Productivity of solar still was increased by 36 % by employing PCM
Ellapan et al. 2023 [131]	Paraffin wax/Ag nanoparticles/ Ricinus communis leaves extracts	Solar still	49.5 °C, 178 J/g	Solar still production enhanced by 124 % and efficacy 52 % using PCM
Paravate et al. 2021 [132]	Hexadecane/poly (4-methyl styrene-co-divinyl benzene)/ TiO2 nanoparticles	Photocatalytic degradation of dye in industrial water	17.5 °C, 174 J/g	TiO_2 decorated PCM capsules showed good photocatalytic activity

Baniasadi et al. developed a smart multifunctional textile using polyethylene glycol (PEG), a phase transition polymer, and electrospun nanofiber mats to improve biomedical function. The textiles also included gelatin and curcumin for improved biomedical function. The electrospun nanofibers showed an ordered random shape, exceptional mechanical properties, and excellent phase change performance. The electrospun fibers had an average diameter of 220–370 nm, tensile strength of 10–30 MPa and a latent heat of 61.7 J/g. Further, the curcumin-loaded fibers released curcumin by initial burst followed by sustained release over a week, presenting significant antioxidant activity of 81.2 % after 24 h.

Liang et al. created a flexible solid–solid phase change material (PCM) covered by self-crosslinking polyethylene glycol (PEG) with a highly reactive silanol group created by reaction with 3-isocyanatopropyltriethoxysilane (IPTS). Using a scalable dip coating process, the solid–solid PCM coating was used to enclose polymer textiles decorated with silver nanowires (AgNWs). The phase change textiles had an EMI shielding efficiency of over 72 dB and an energy storage density of 86.6 J g1. The textiles also exhibit a flexible thermal response, high joule heating efficiency, excellent heat storage and release, efficient heat

Fig. 13. PCM-Enhanced Textiles for Improved Thermal Comfort:

dissipation, and infrared anti-counterfeiting behavior.

To solve poor thermal conductivity and PCM leakage, Liu et al. incorporated multiwall carbon nanotubes (MWCNTs) into polyacrylic nitrile (PAN)/PEG composite phase change nanofibers. According to the results, the electrospun PAN/PEG composite nanofibers with 10 wt% MWCNTs loading demonstrated outstanding thermal reliability, moderate melting enthalpy (78.3 J/g), and improved phase transition material leakage. These membranes have the potential for thermal energy storage and temperature-controlled textile applications since they may also be involved in thermal energy modulation.

Renard et al. presented the thermal properties of multilayer protective garments, focusing on the impact of phase-change material (PCM) incorporation on the actual heat transmission. Octadecane macro capsules containing multilayer textile assemblies and reference textiles containing polypropylene macro granules were compared over heat transmission. It was observed that the PCM-containing assemblies increased the temperature by 12 °C over a more extended period than reference assemblies.

Yan et al. developed a unique tri-mode all-weather personal thermal management textile (TAWT) that combined radiative cooling, solar heating, heat storage and release using PEG through a two-step scalable electrospinning technology. TAWT generated a temperature difference of 9.2 °C and 13.1 °C in cooling mode compared to traditional textiles and the human body due to its midinfrared emittance of 93.2 % and solar reflectance of 96.6 %. In heating mode, with 82 % solar absorptivity and 67.8 % lower infrared emissivity, the TAWT prevented overcooling by 10.9 °C compared to human skin. The enthalpy of TAWT 81.1 J/g created an additional temperature drop of 3.9 °C in high humidity weather for the radiative cooling shortage. The TAWT had positive wearability characteristics like air and moisture permeability, stretchability, and launderability, making it a promising starting point for creating valuable textiles.

Khosravi et al. produced a fatty acids/nano Al-based/wool composite for the first time using in situ production. The experimental results showed that the ideal melting and solidifying temperatures for the intended application are 36.59 and 29.58 °C, with responsive enthalpies of 59.22 and 52.08 J/g, respectively. The composites also exhibited outstanding antibacterial and antifungal properties, good methylene blue degradation when exposed to sunshine, reduced alkali solubility, increased shrinkage resistance, and decreased water absorption.

The summary of the literature reports discussing various applications of PCMs in textile-based products is given in Table 10.

Summary

PCMs are used to design textiles that possess thermal regulation capability. Microencapsulated PCM capsules are mainly used for textile applications, whereas macro encapsulated PCM packets are also used in some cases. Further, studies showed that intelligent textiles with multifunctional properties like electromagnetic shielding, antioxidant, anti-bacterial and photocatalytic activity could also be prepared by adding nanoparticles and PCMs for biomedical, defense and household applications. Electrospinning, dip coating, or soaking methods are mainly used to add PCM to the textiles. The thermoregulating textiles were found to maintain the temperatures of the human body in the comfortable zone when exposed to higher/lower ambient temperatures by reducing the heat transfer rate.

3.10. Waste heat recovery

Waste heat recovery applications rely significantly on phase change materials (PCMs). They aid in efficiently capturing, storing, and using surplus heat produced by various industrial processes, engines, structures, and equipment. In cement plants, glass factories, and steel mills, PCMs are included in waste heat recovery systems. They reduce energy usage by storing waste heat and releasing it when required for other activities. To increase fuel efficiency or power auxiliary systems, PCMs can absorb waste heat from car engines and exhaust systems and transform it into usable energy. PCMs improve energy efficiency and dependability in data centers and electronics by managing waste heat produced by servers and electronic components. Utilizing the waste heat generated in buildings requires the use of PCMs. Various industries that generate waste heat that can be utilized using PCMs are shown in Fig. 14.

He et al. developed a novel and multifunctional CNF-CNT-Fe_3O_4-Paraffin wax-Glycerol/ PAAm organohydrogel denoted as CCFP-G/P with multiple integrated properties. It is produced using the Pickering emulsion method and UV-initiated polymerization, with phase change microspheres resembling rambutans and a polyacrylamide (PAAm) skeleton. The utilization organohydrogel in a thermoelectric generator could harness the waste heat and provide a remarkable output voltage of 518.0 mV and output current of 86.3 mA through thermoelectric conversion. The organohydrogel has thermal management capability, waste heat utilization, thermal-electric conversion, wide temperature sensing range, low detection limit, and long-term environmental stability.

Luo et al. recovered waste polyvinyl chloride (PVC) as SiC skeletons to make green phase change composites (PCCs) for waste heat recovery. The proposed PCCs with paraffin wax PCM OP44E exhibit a high retention ratio of latent heat up to 91.1 % and a thermal conductivity of 2.4 W/m. K, supporting the controlled expansion and impurity removal methods. They offer better solar-thermal energy storage rates and cut the time needed for charging and discharging by 21 % and 41.1 %, respectively.

Zhang et al. developed a CO_2-based waste heat recovery (WHR) system with cascade latent thermal energy storage (CLTES) to ensure efficient and continuous operation during the ship's journey. The results show that pump and turbine efficiency must be compromised to reach the required power capacity, with turbine efficiency having a more significant impact on the proposed system's increase in thermo-economic performance than pump efficiency. The daily net power generation and heating capacity of the proposed system were 5356 kWh and 6958 kWh which are 19.1 % and 7.9 % higher than those of the traditional WHR system, and the proposed system's levelized exergy cost is 17.9 % lower than that of the reference cycle.

Yang et al. designed a cascade latent heat thermal energy storage (LHTES) for recovering industrial waste heat at medium temperatures. The only high melting PCM erythritol (melting $\sim$ 118 °C) based system cannot absorb the heat at temperatures lower than its melting point. So, the cascade system was designed using a PCM melting point of 60 °C, which could boost waste heat recovery efficiency from 15.8 % to 63.4 % compared to a single-stage erythritol-based system under various operating conditions. The average supply heat temperature of the cascade system can also be increased from 37 °C to 53.6 °C by tuning the flow rate.

The BiOI-MEPCM, a new type of multifunctional phase-change microcapsule, was developed by Jing et al. as a workable solution for waste recovery and wastewater treatment. The microcapsules were first prepared to take n-docosane as core PCM and SiO_2/Fe_3O_4 as composite shell through in situ interfacial polycondensation and with Fe_3O_4 nanoparticles assisted as a Pickering emulsion stabilizer followed by BiOI nanosheets deposition on the SiO_2/Fe_3O_4 composite shell. The microcapsules possessed 46.8–115.7 J/g enthalpy due to docosane core for waste heat absorption, and the deposited BiOI nanosheets enabled photocatalysis, eliminating organic contaminants in wastewater, and the magnetic response produced by Fe_3O_4 nanoparticles during magnetic separation revealed high separability and recyclability. This study provides a viable technique for designing and fabricating multifunctional phase-change microcapsules for waste heat recovery and wastewater treatment.

The form of a PCM container significantly influences its melting behavior and heat storage capability. Qin et al. modeled the melting behavior and heat storage capability in PCM storage containers with different forms, including rectangular shapes and concave folded sides.

Table 10
Summary of Research on Phase Change Materials (PCMs) for Thermal Management in Textiles.

Author	PCM/shell	Method/application	Properties	Remarks
Kumar et al. 2023 [133]	Poly ethylene glycol/graphene oxide/cotton	Cotton fabric with thermal regulation and UV blocking	58 °C, 37 J/g	UV protection factor of GO deposited PEG grafted cotton fabric is increased.
Majd et al. 2023[134]	Inertek 26P (vegetable based wax PCM micro encapsulated in polymer shell)	PCM capsules bind to three biobased textiles using acrylic binder Acronal® 32D / thermo regulating textiles	MPCM-25.25 °C, 194.9 J/g Cotton with 20 % MPCM-25.5 J/g	Recycled cotton coated with PCM capsules showed best performance than other textiles
Kong et al. 2023[135]	Water borne polyurethane PCM PEG2000 (WPUPCM)	Design of intelligent textiles	WPUPCM-37 °C, 74.7 J/g	Textiles prepared with stable color visibility and thermal regulation
Song et al. 2023[136]	Polyethylene oxide-ferric oxide (PEO-Fe3O4)/ Poly vinyl alcohol sheath textile	Smart textiles prepared using coaxial electrospinning /Surface cross linking for electronics	PEO- 65.9 °C, 137.1 J/g, PCM fibers- 63.1 °C,93.1 J/g	Thermoregulating textile with 20 wt% Fe3O4 showed electromagnetic shielding
Baniasadi et al. 2023 [137]	Polyethylene glycol/ poly caprolactum/ gelatin-curcumin	Electrospinning/ Multifunctional textile for biomedical applications	33.2 °C, 61.7 J/g,	Curcumin loaded thermoregulating PCM composite fiber showed good antioxidant activity
Liang et al. 2023[138]	Solid-Solid PCM (PEG cross linked with silane)-silver nano wires/ PET textiles	Textiles dipcoated with silver nanowires and PCM for electromagnetic interference shielding	62 °C,86.6 J/g	0.26 mm thick PCM coated textile showed 72 dB electromagnetic shielding
Liu et al. 2023 [139]	PEG/Poly acrylonitrile-MWCNT composite nano fibers	Electrospinning/ Temperature regulating textiles	61.1 °C, 78.9 J/g	PCM based electrospun MWCNT incorporated nanofibers showed good thermal regulation
Renard et al. 2023[140]	Octadecane/ polyurethane macro capsules (Microtek labs)	Multilayer protective clothing for contact and radiant heat	28 °C, 185 J/g	PCM contained textiles slowed down heating compared to reference PP textiles
Yan et al. 2023 [141]	PEG/cellulose acetate- TAC (Ti_3AlC_2)nanoparticles-polyamide (PA6)	Coaxial electrospinning/ Trimode all-weather personal thermal management textile(TAWT)	34 °C, 81.1 J/g	TAWT showed cooling effect with temperature 13.1 °C and 9.2 °C lower than human skin and cotton fabric
Khosravi et al. 2023[142]	Lauric-myristic acid eutectic PCM/Nano (Al $(OH)_3$/ Al_2O_3)/Wool fabric	Soaking method/Multi functional wool fabric	36.59 °C,59.22 J/g	Thermal regulating wool fabric prepared with shrink resistant, smoke suppressant, antibacterial and photocatalytic properties

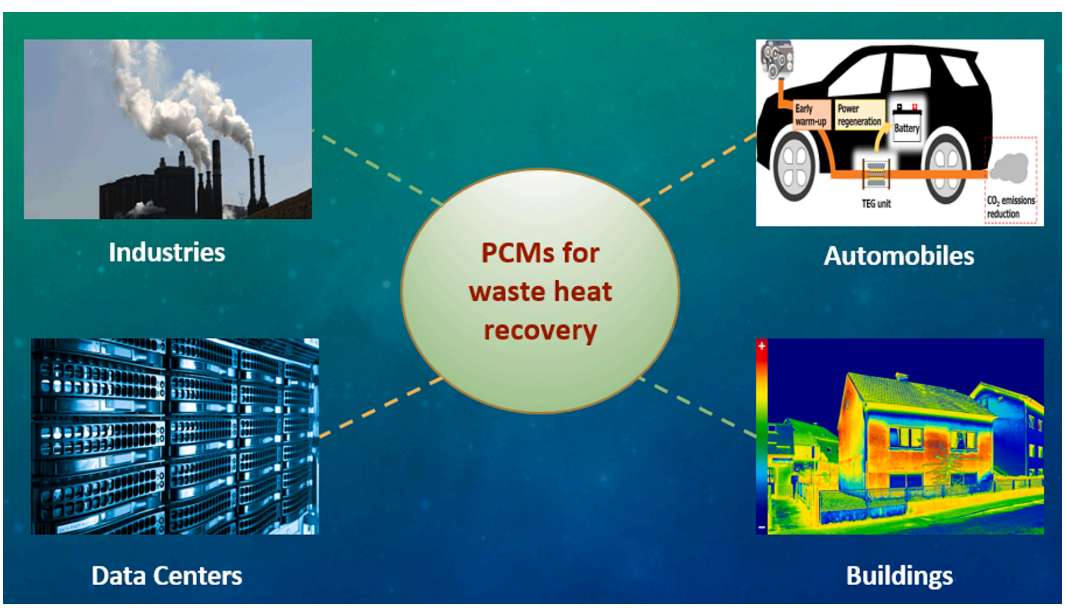

Fig. 14. Utilizing Phase Change Materials (PCMs) for Waste Heat Recovery in Various Industries:

The PCM container design angle substantially influences natural convection strength, PCM melting time, and energy storage rate. The protruding-shaped container with an angle of 133.8° displays the quickest melting time of 4,645 s when compared to the rectangular chamber used as the baseline with an angle of 90°. This work may be used as motivation to develop PCM storage geometries for industrial applications that efficiently recover waste heat.

Sun et al. developed and enhanced a novel composite PCM based on expanded graphite (EG), carbon nanotubes (CNTs), and sodium acetate trihydrate (SAT). By adding urea 0–10 wt% to improve the melt uniformity of SAT, the composite PCM's phase change effect was operational above 50 °C. The porous network made by EG eliminated the liquid mobility of PCM, and the addition of CNTs may significantly increase the heat conductivity of the composite PCM. The melting enthalpy of urea-SAT mixture was 250.5 J/g, and addition of 4 % DHPD helps in the rapid crystal growth rate by forming more nuclei. So, the composite PCM of Urea-SAT/EG/CNF shows high latent heat of 180.1 kJ/kg and high thermal conductivity of 6.904 W/m.K with supercooling reduced to 0.6 °C.

Zhang et al. developed three different kinds of magnetic phase-change microcapsules with n-docosane as the phase-change material core and crystalline phase-tunable $CaCO_3$ as the shell, in which Fe_3O_4 nanoparticles were embedded to give the microcapsules magnetic responsiveness. The magnetic microcapsules had spherical, rhombohedral, and fusiform morphologies, followed by phase-change enthalpies of 135.3, 87.1, and 48.7 J/g, respectively. Moreover, the PCM microcapsules showed maximum adsorption capacities of 703.1, 862.3, 924.0 and 514.7 mg/g for the removal of Cu^{+2}, Cd^{+2}, Cr^{+3} and Fe^{+3}, respectively.

Gurbuz et al. conducted an experimental investigation on melting phase change material (PCM) in a latent heat storage (LHTS) system used to store the exhaust waste heat energy of a standard SI engine. The PCM heat exchanger (PCM_hex) was used to store and melt the PCM RT55, and the volume control of the movable top surface of the cylindrical PCM_hex was performed by a linear actuator with a 1000 N capacity. The results showed that the RT55 with the volume-controlled PCM_hex melts more effectively and has an improved energy storage capacity of around 4.57 %.

A unique plate heat exchanger-based air preheating system was created by Soliman et al., employing nano-enhanced phase change materials (NEPCM). Using data from experiments, a thorough thermal model was created and verified. The melting and solidification processes in the NEPCM domain are combined with the model's turbulent fluid flow of engine exhaust gasses. Using five wt% of SiO_2, Al_2O_3, and CuO nanoparticles decreased the charging time by 34.88 %, 30.23 %, and 25.58 %, respectively. The literature reports on waste heat utilization from various industries using PCMs are summarized in Table 11.

Summary

The waste heat generated by industries, automobiles, buildings, and data centers can be recovered using the thermal energy storage capacity of PCMs. A study revealed that rambutan-shaped PCM microspheres enabled thermal electric generators to harness a considerable voltage of 518.0 mV using waste heat. A PCM-based cascade latent thermal energy storage system for waste heat recovery in ships increased the power generation and heat capacity by 19.1 % and 7.9 % compared to traditional waste heat recovery systems. A study showed that the cascade latent heat storage system showed 15.8 % to 63.4 % waste heat recovery efficiency compared to a single PCM system. Further, the application RT55 PCM for heat recovery of an SI engine revealed that the heat storage capacity was increased by 4.57 %. Nanoparticle-enhanced PCMs application in unique plate heat exchanger-based air preheating system decreased charging time. Silica nanoparticles showed a better reduction in charging time than Al_2O_3 and CuO nanoparticles.

4. Advanced application of PCMs

Phase change materials can be used in advanced applications like artificial intelligence, spacecraft thermal management, and hydrogen storage.

4.1. PCMs application in artificial intelligence

Artificial intelligence (AI) applications did not directly use phase change materials (PCMs). PCMs, however, can indirectly influence AI systems by helping to regulate the heat and energy consumption of the hardware that drives AI applications. AI systems produce a lot of heat when running, especially those that use powerful GPUs or TPUs. To manage the thermal loads and guarantee that these hardware components run at ideal temperatures and retain peak performance, PCMs can be integrated into cooling systems. AI servers and infrastructure are housed in data centers [153,154], which need a lot of energy to cool them. Data centers can manage and retain extra heat during low demand and release it during high demand by using PCMs in the cooling systems, which optimizes energy use and lowers cooling costs [155]. The thermal management capabilities of AI systems at the edge, such as those in IoT devices or autonomous vehicles, are frequently constrained. These devices can incorporate PCMs to control temperatures, ensuring they perform well in various environmental circumstances. AI models and algorithms can run more efficiently on hardware with low power and passive cooling.

4.2. PCMs application in spacecraft technology

When it comes to spacecraft technology, where severe temperatures and thermal control are crucial, phase change materials (PCMs) have a variety of uses. To safeguard spacecraft during re-entry into Earth's atmosphere, a thermal protection system uses PCMs [156]. In high-temperature phases, they retain heat, releasing it gradually to avoid overheating. To control body temperature in the harsh vacuum of space, where temperatures vary greatly, PCM-infused fabrics are utilized in astronaut spacesuits. To provide a constant temperature environment for delicate equipment and electronics, PCMs are used in spacecraft for thermal management [157,158,159]. For long-duration space missions, PCMs are utilized in food storage containers to maintain the temperature of perishable foods. PCMs can increase overall energy efficiency by storing extra heat produced in spacecraft and releasing it as needed.

4.3. PCMs application in hydrogen storage

The potential use of inorganic phase change materials (PCMs) in hydrogen storage has attracted interest. Mainly inorganic PCMs that are efficient in storing and releasing hydrogen gas include metal hydrides and chemical hydrides [160,161,162]. Like magnesium hydride, metal hydrides have a large hydrogen storage capacity because they can absorb and release hydrogen through reversible chemical reactions. Chemical hydrides like sodium borohydride can hydrolyze and then regenerate hydrogen gas. Due to their high hydrogen density, these inorganic PCMs are ideal for small, effective hydrogen storage devices. However, the demand for appropriate catalysts and ideal operating conditions are obstacles. The performance and viability of inorganic PCMs for hydrogen storage in various applications, such as fuel cell cars and portable hydrogen devices, are still being researched.

5. Opportunities, challenges and limitations of PCM applications

Phase Change Materials (PCMs) have various opportunities and advantages but also limitations and restrictions.

5.1. Opportunities

Energy Efficiency: PCMs can improve various systems' energy efficiency, reducing energy use and associated expenses. This can significantly benefit buildings, industrial processes, and renewable energy applications.

Thermal Comfort: By stabilizing indoor temperatures and lowering the requirement for heating and cooling in building applications, PCMs can enhance thermal comfort.

Environmental Sustainability: By consuming less energy, PCMs help to maintain a healthy environment by minimizing greenhouse gas emissions and energy waste.

Waste Heat Recovery: By allowing waste heat to be captured and used again, PCMs improve the overall effectiveness of energy systems.

Integration of Renewable Energy Sources: By storing extra energy for later use, PCMs can make integrating renewable energy sources like solar and wind power easier.

Table 11
Summary of Research on Phase Change Materials (PCMs) for Waste Heat Recovery Applications.

Author	PCM/shell	Method/application	Properties	Remarks
He et al. 2023 [143]	3 Paraffin wax (PW)/cellulose nanofibrils/carbon nanotubes/ Fe_3O_4	Pickering emulsion and UV-initiated polymerization/waste heat recovery	PW1- 43.9 °C, 60.5 °C, 57.75 J/g PW2- 30.1 °C, 50.9 °C, 57.25 J/g PW3- 21.2 °C, 38.3 °C, 31.24 J/g	Rambutan shaped PCM based composite could turn waste heat to output voltage of 518.0 mV
Luo et al. 2023 [144]	Paraffin wax (OP44E)/SiC composite	Vacuum infiltration/waste heat recovery	43 °C, 227.15 J/g	Charging and discharging time were reduced by 21 % and 41.1 % using PCM composite in packed bed TES
Zhang et al. 2023[145]	PCM1-LiNO3-NaCl, PCM2-D-Mannitol, PCM3-Oxalic acid	Shipboard waste heat recovery system	PCM1-208 °C, 369 J/g, PCM2-165 °C, 300 J/g, PCM3- 105 °C,356 J/g	Levelized exergy cost of cascade TES system with three PCMs was 17.9 % less than reference system
Yang et al. 2023[146]	Paraffin wax(R60) And erythritol	Recovery of medium temperature industrial waste heat	R60- 59.4 °C, 186.7 J/g Erythritol- 118.8 °C, 333.7 J/g	Cascade latent heat storage system improved heat recovery by 15.8 % to 63.4 %
Jing et al. 2023 [147]	n-Docosane/SiO_2/Fe_3O_4/bismuth oxyiodide (BiOI)	Sol-gel/ waste heat recovery	43.63 °C, 46.18–115.7 J/g	Multifunctional phase change microcapsules were prepared for waste heat recovery
Qin et al. 2022 [148]	Paraffin wax (VWR, Singapore)	Waste heat recovery from industrial exhaust gases	52.54 °C, 126.2 J/g	Geometry of PCM container proved to play role in phase change rate of PCM
Sun et al. 2022 [149]	Sodium acetate trihydrate-urea/ expanded graphite/carbon nanotubes	Waste heat recovery	55.8 °C, 180.1 J/g	The PCM composite had high thermal conductivity and latent heat storage capacity
Zhang et al. 2022[150]	n-Docosane/CaCO3/Fe3O4	Waste heat recovery and heavy metal ion recovery	45.1 °C, 135.3 J/g	Capsules prepared with different surfactant had different geometries and latent heats
Gurbuz et al. 2022[151]	Paraffin RT55	Exhaust waste heat recovery of SI engine	55 °C, 170 J/g	Rate of fuel energy stored in PCM based system was around 4 %
Soliman et al. 2021[152]	Lauric acid and paraffin wax	waste heat recovery from exhaust gas energy in diesel engines	Lauric acid- 43.5 °C, 187.21 J/g Paraffin wax- 54.22 °C, 278.8 J/g	5 wt% SiO2 nanoparticles reduced the charging time by 34.88 % which was higher than Al2O3 and CuO particles

5.2. Challenges

High Cost: The price of some high-performance PCMs may prevent their broad adoption.

Material Selection: With so many different materials on the market, each with unique qualities, selecting the best PCM for a given application can be difficult.

Thermal conductivity: PCMs’ generally lower thermal conductivity may impact heat transfer rates than conventional building materials.

Limited Temperature Range: Due to their limited temperature range for phase changes, PCMs are less suitable for large temperature swings applications.

Volume Expansion: During phase change, some PCMs can expand, which could lead to structural problems in some applications.

5.3. Limitations

Cost: Not all materials or systems may be compatible with PCMs, so careful integration and design are necessary.

Limited Cycle Life: Some PCMs’ performance may suffer from frequent phase changes over time.

Weight: The weight of PCM systems might be an issue in particular applications, such as cars.

Slow response time: PCM response times may be slower than those of conventional heating and cooling systems.

Space Needed: Particularly in retrofit projects, the space needed for PCM integration in applications like buildings can be a problem.

Continuous research and development are frequently required to address these issues and constraints to produce more efficient, high-performance PCMs and improve their integration into other systems. Despite these difficulties, PCMs are essential for enhancing various industries’ thermal control and energy efficiency.

6. Conclusions

This review paper presented a discussion on the application of phase change materials in significant sectors of industries. Overall, solid–liquid PCMs are predominantly explored for their application in various fields compared to solid–solid PCMs. More organic PCMs are explored than inorganic PCMs.

1. PCMs in buildings and construction are applied mainly to building components like concrete, bricks, walls, floors, roofs, windows, and wall paints. Interestingly, solid–solid PCMs have been explored for application in building windows.
2. PCMs are applied in automobiles for battery thermal management in electric vehicles, thermal regulation in vehicle cabins, anti-freezing tires and increasing energy savings in refrigerated trucks.
3. PCMs in the biomedical field are mainly used for designing intelligent drug delivery systems for cancer therapy, increasing bio sensors efficiency, vaccine carrier boxes and neonatal coolers.
4. PCMs are very useful in storing the heat from the sun for use in concentrated solar power plants, increase energy efficiency in solar energy-based devices like solar heater, solar panels etc.
5. PCMs are crucial in thermal management of electronics like photovoltaic cells, computers, and data centers. Solid-solid PCMs help design data storage devices due to their reversible crystalline to amorphous phase transitions.
6. PCMs are helpful in power generation by utilizing them as sinks for thermoelectric generators, using heat energy from the sun to generate steam in concentrated solar power plants, power generation from waste heat recovery and boosting the power generation from photovoltaic cells by providing proper cooling.

7. Thermal-sensitive foods like chocolates, fruits, vegetables, dairy products and ice creams are transported and stored in the temperature-controlled environment using PCMs
8. Using solar stills, the application of PCM can enhance fresh water production from salt water. The pollutants in industries' wastewater streams could be degraded using nanoparticle-decorated phase change microcapsules.
9. PCMs are applied in textiles to design thermoregulating personal wear, sportswear, bedding, furniture, and intelligent biomedical clothing.
10. Waste heat from industries, automobiles, buildings and data centers could be stored and utilized efficiently using PCMs

Overall, due to their adaptability, PCMs are helpful in a variety of applications and have the potential to increase thermal comfort, decrease waste, and improve energy efficiency in a variety of industries, thereby reducing greenhouse gas emissions and protecting the environment.

CRediT authorship contribution statement

Vennapusa Jagadeeswara Reddy: Writing – original draft, Formal analysis, Data curation, Conceptualization. **Mohd Fairusham Ghazali:** Writing – review & editing, Visualization, Validation, Resources, Project administration, Funding acquisition. **Sudhakar Kumarasamy:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Investigation.

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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