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REVIEW ARTICLE

Sustainability in thermal applications using bio-phase change materials: a review

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Abstract

Bio-based phase change materials offer a promising solution for environmentally friendly thermal energy storage systems. Bio-phase-change materials exhibit desirable properties, such as high latent heat, low vapor pressure in the melt, chemical stability, safety, and cost-effectiveness. Unlike their petroleum-based counterparts, bio-phase change materials, being entirely hydrogenated, pose a significantly lower risk of oxidation even after multiple solidification and melting cycles. Moreover, their production can be scaled up using readily available, inexpensive, and biocompatible sources such as animal fat mixtures and oils. This paper provides an extensive review and analysis of studies on the development of bio-phase change materials (BPCMs), the design of bio-supported matrix configurations, phase change procedures, and their integrated use, manufacture, and application in thermal energy storage systems. Its purpose is to objectively examine the viability of different kinds of BPCMs in thermal energy storage applications, emphasizing their life-cycle impacts and prospective advantages, while recognizing existing problems and limitations. This work advances our understanding of how BPCMs can be used efficiently in various thermal energy storage systems.

Keywords: Bio-PCM, BPCM, sustainable materials, eco-friendly, thermal energy storage

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1. Introduction

As a consequence of rapid economic growth, energy consumption has soared to unprecedented levels. Similarly, fossil fuels have a finite supply and cannot meet demand. Therefore, scientific organizations and energy prioritize clean energy sources [1]. Thermal energy storage improves the consumption of energy over many thermal segments by identifying an imbalance between energy consumption requirements and their usage [2, 3]. Thermal energy storage has gained significant traction over the years by harnessing the potential of phase change materials (PCMs) [4]. As a result, many researchers are keen to develop the most suitable energy mediums for thermal energy storage, aiming to meet supply requirements while minimizing reliance on conventional energy sources [5-7]. Petroleum-based PCM a unique material capable of storing thermal energy and releasing it at a steady temperature while maintaining a high heat of fusion [8]. After multiple heating and cooling cycles, the physical and chemical characteristics of PCMs remain unchanged. When selecting an appropriate substance for heat energy storage, several variables must be considered, these includes cost, storage density, toxicity, and reliability. Currently, there is a growing interest in researching the potential applications of PCMs capable of absorbing and releasing thermal energy during phase changes [9]. PCM temperatures typically range from-5 to 190°C, depending on material and application [10]. These PCMs (hydrocarbons) are commonly classified into three types based on their chemical formulations: (a) inorganic PCMs, (b) organic PCMs, and (c) eutectic PCMs [11]. The optimal characteristics of the chosen PCM on commonly used thermal energy storage systems include an appropriate melting temperature [12], transferred heat capacity, sufficient

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heat of fusion, thermal stability with low rates of super-cooling, acceptable economic feasibility [13], and self-nucleating characteristics with no separation.

Several studies have analyzed the thermal properties of inorganic, organic, and eutectic PCMs for various purposes. Inorganic PCMs have very good heat capacity and thermal conductivity ranging from 0.3 to 1 W/m•K over a very broad temperature range [14, 15]. However, inorganic PCMs have a number of limitations, such as a tendency toward toxicity and excessive supercooling. Organic PCMs are one of the best choices for storing thermal energy because of their very low vapor pressure, high storage energy capacity, chemical stability, self-crystallizing nature, and commercial availability [16, 17].

Regardless of innovations, the overall energy problem requires environmentally friendly solutions. Over 40% of global petroleum energy production is used for residential lighting and heating, contributing to 33% of overall annual greenhouse gas emissions. Inorganic PCMs are petroleum-based derivative products commonly used for thermal energy management. However, the innovations in question entail not only environmental but also economic problems, such as harmful spillover effects and price instability driven by global politics. In any event, control of energy use across different applications is crucial. Innovations play a significant role in controlling temperature variations and maintaining a constant indoor temperature. To protect natural ecosystems from harm, it is crucial that innovations be environmentally friendly. BPCMs appear to be innovative solutions that can meet the required criteria because of their specific features, including the low level of pollution, energy storage capacity, stability, volumetric change, and sustainability [18-21].

Consequently, this research investigated ecologically viable PCMs, including polyols, fatty acids, esters, and eutectics formed from used vegetable oils, by-products, wood grain, and animal fat. The review considered 73 research articles published from 2014 to 2024. Ecologically viable PCMs are distinct from other PCMs by their ability to absorb or release thermal energy during the solid-to-liquid phase-change process. Ecologically viable PCMs are notable for their ability to absorb and release heat without causing environmental pollution. They are not only thermally stable but also non-toxic and thus environmentally viable.

For a detailed review, this study classifies BPCMs into two groups based on the material used for their synthesis. An objective-based review of the application of different types of BPCMs for thermal management and thermal energy storage systems in buildings will be presented, along with the nominal benefits, limitations, and challenges of such applications.

2. Applications of employing BPCMs

Although inorganic paraffinic PCMs have a variety of applications, their poor thermal conductivity is a major disadvantage. Additionally, their flammability renders them unsuitable for use in the building industry. Furthermore, conventional PCMs have a considerable carbon emission impact [18]. To address these problems, bio-based phase change materials – organics and composites – known as BPCMs have been developed and are widely utilized in thermal energy storage (TES) systems. BPCMs can be derived from sustainable resources, including plant extracts, agricultural waste, biomass, animal fat, vegetable oils (e.g., coconut, palm, and palm kernel oils), and other natural resources and biopolymers. BPCMs include esters, alcohols, fatty acids, glycols, and other compounds. These PCMs have attracted great attention due to their ability to increase energy efficiency, but, unlike traditional petroleum PCMs, they cause less environmental impact.

In the following sections, the most relevant research on different types of BPCMs will be reviewed and analyzed. Figure 1 illustrates the flowchart of the classification and main applications of BPCM presented in this study.

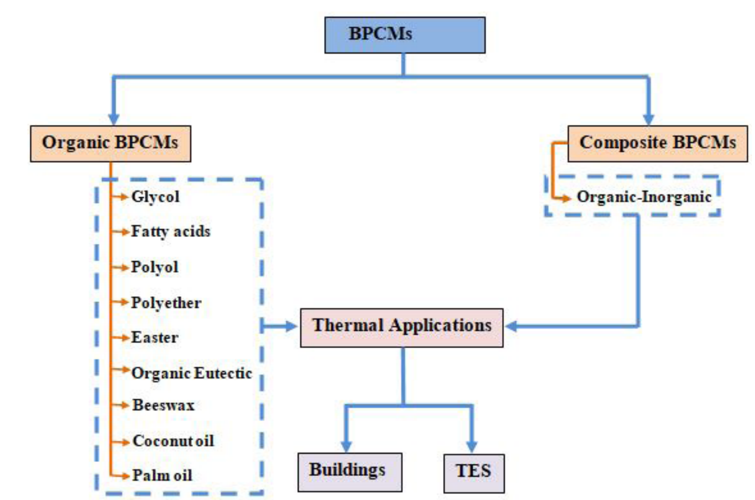

Figure 1. Flowchart of the classification and main applications of BPCM presented in this study.

Organic-based BPCMs: Nearly all organic-based BPCMs are derived from sustainable sources, commonly from animal fats and vegetable oils such as coconut, palm, and palm kernel, as well as beeswax. The range of melting temperatures of these materials is extensive, making them suitable for various applications. This review focuses on organic BPCMs suitable for integration into diverse applications.

Thermal energy management applications in buildings: In 2018, Boussaba et al. [22] used coconut oil as a natural and cost-effective

BPCM for increasing thermal inertia in buildings' envelope structures. The BPCM was combined with a composite matrix prepared from cellulose fibers and natural clay. A direct immersion procedure, without any vacuum treatment, was employed to incorporate the BPCM into the matrix. Thermal, physical, and chemical evaluations indicate that the produced BPCM can be used as a building material in passive TES systems to increase thermal inertia.

In 2019, Boussaba et al. [23] manufactured BPCM from palm kernel oil with 74.35 J/g heat capacity and 26.35 °C melting point for use in TES technology in buildings. Cellulose fibers and organic clay were used to support the BPCM, as these materials are inexpensive and environmentally friendly. Surface tension and capillary forces enabled the effective inclusion of about 53 wt.% BPCM in the system using the direct absorption approach. As illustrated in Figure 2, DSC results suggest that the energy storage capacities of the proposed BPCM are suitable for building applications. Also, the addition of graphite enhanced the thermal conductivity without altering its chemical stability.

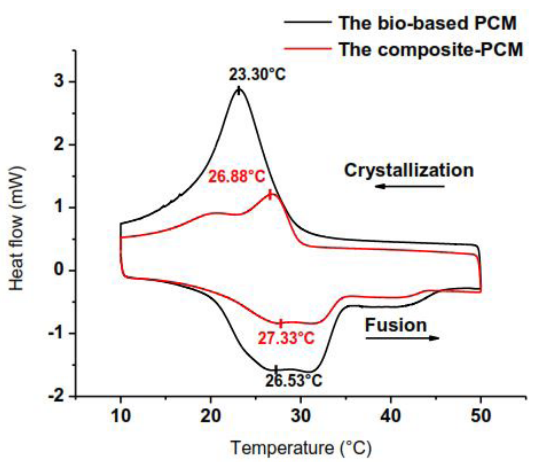

Figure 2. The DSC curves for the BPCM and the composite-PCM [23]

In 2021, Hekimoglu et al. [24] were able to synthesis two kinds of organic carbon by carbonization and chemical activation of WS, which acted as a lightweight and absorptive, economic and environmentally friendly supporting matrix. The aim of this research was to evaluate the potential application of the synthesized WS carbons (WSC) and activated WS carbons (AWSC) as stabilized materials to enhance the thermal conductivity of MP, which can be considered an appropriate BPCM.Using chemical activation, the pore size and surface area of WS increased by factors of 1.44 and 1.47, respectively. The DSC measurements illustrated that the melting temperatures of AWSC/MP and WSC/MP was 26.65 °C and 26.27 °C. The results showed that AWSC/MP and WSC/MP exhibited thermal conductivity values approximately 1.58 and 1.9 times higher than those of MP alone, respectively.

Zhao et al. [25] explored in 2022 BPCM materials to minimize the total consumption of energy in buildings, by incorporating polyethylene glycol (PEG)/organic diatomite (O-Dt) as a BPCM and wood fiber (WF)/high-density polyethylene (HDPE) as the supporting structure. The BPCM demonstrated a considerable thermal storing capacity approximately 60.42 J/g, and regulated temperature between 12 °C and 15 °C. Compared with 0% BPCM, the thermal conductivity of 20% BPCM was 26.7% higher. In addition, when 5% BPCM was loaded into supporting structures, both their strength and hydrophilic properties were enhanced.

In 2022, Naresh et al. [26] developed a BPCM by vacuum-impregnation porous fly ash (FA) stones with n-dodecanoic acid, as shown in Figure 3. The used BPCM was leak stable at 85 °C and thermally stable at 150 °C. After a thousand cycles of temperature assessment, the BPCM achieved a remarkable thermally stable retention of 96.76%. The effective permeation of BPCM into FA stones was also attributed to BPCM's low thermal conductivity (0.1702 W/mK). This developed BPCM is a viable candidate for use in passive TES in buildings. In another study, Naresh et al. [27] used similar strategy to develop a novel BPCM using hexadecanol as the PCM with FA as the supporting matrix. It was seen that after 1000 melting and freezing cycles, the thermal stability of the BPCM remained relatively good, with a melting enthalpy of 114.41 kJ/kg. In addition, the BPCM was demonstrated to have leak stability of above 85 °C, which exceeds the PCM's working temperature. The BPCM has a thermal conductivity of 0.3397 W/m K, making it suitable for blocking solar heat from entering a building.

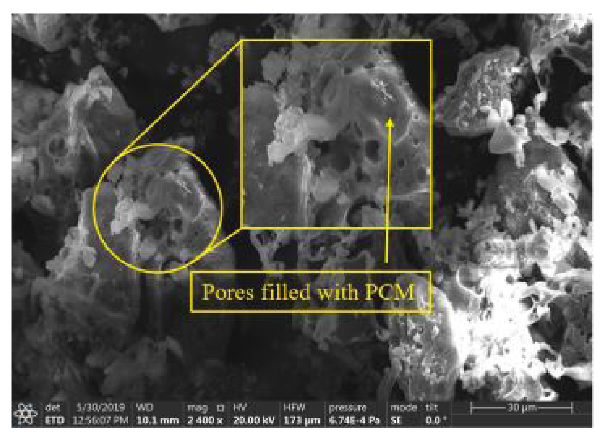

Figure 3. FESEM image of the BPCM [26]

In 2022, Choi et al. [28] investigated the acoustic and thermal specifications of a bio-based microencapsulated PCM (MPCM) blended with coffee wastes, and the composite was used as a building insulation material. DSC analysis revealed a latent heat of 3.8 J/g for samples containing 10% MPCM. Furthermore, as the MPCM ratios increased, the temperature decreased more slowly due to the MPCM's ability to retain heat over time. An impedance tube test demonstrated that specimens containing MPCM exhibited a higher sound absorption coefficient and improved acoustic performance in the mid-frequency range. Consequently, the composite can be considered an environmentally friendly insulation material for construction with favorable thermal and acoustic properties.

In 2014, Biswas and Abhari [29] produced BPCM by capturing organically produced fatty acids and glycerides in the pellets of high-density polyethylene (HDPE). They assessed the efficacy of the BPCM in a building-envelope application. These pellets were blended with cellulose insulation and applied to the exterior walls of an experimental construction site under hot and humid conditions. The building's structure subsequently undergoes a months-long series of examinations. The test walls were computationally modeled to evaluate the effect of PCM-HDPE pellets on the walls' heating and cooling loads. The power consumed by each used load is presented in Figure 4. After being tested on experimental data, the approach was used to generate annual forecasts based on locally obtained climate data.

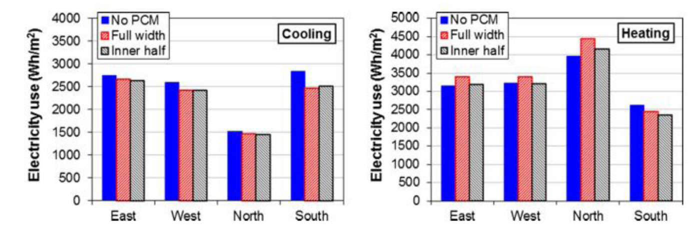

Figure 4. Calculated annual cooling(left)and heating(right) electricity use with different PCM configurations [29]

In 2015, Cellat et al. [30] studied the binary combinations of capric acid (CA), myristic acid (MA), lauric acid (LA), and palmitic acid (PA) to identify suitable building material. The phase-change temperature may be adjusted to levels considered safe for humans by altering the relative proportions of different fatty acids. Two binary combinations, CA-LA and CA-MA, were developed to examine their potential use as a BPCM in construction. Both the BPCMs passed the thermal cycling test, indicating thermal and chemical stability. Inclusion of 1 wt.% BPCM reduced the compressive strength of concrete mixtures by 12%. When BPCM levels were increased to 2 wt.%, compressive strengths decreased further.

In 2017, Tor et al. [31] investigated the thermo-physical characteristics and benefits of using fatty ester as a BPCM for an internal environment when incorporated into an office cubicle. In the experimental environment, indoor air temperatures of the 15 m^2 room, surface temperature of BPCM, as well as temperature of the floors, ceilings, and walls were monitored. Various approaches, such as fixing PCM to the ceiling with or without ceiling panels, were considered. The results showed that placing 17 square meters of uncovered BPCM in an area directly exposed to the inhabited space could provide a significant cooling load.

In 2017, Yassine et al. [32] investigated the temperature regulation of a room powered by solar energy and made of special bio-compound walls covered by PCM. The bio-walls were composed of bio-boards named IBS IZOLOX, produced by the Belgian company ISOLHABITAT. The interior of the bio-wall was supplemented with an additional PCM coating to enhance the insulating properties of the room shell. Based on the data presented in this study, the wall in question is capable of increasing thermal comfort and the effectiveness of the operation of the solar room in winter.

In 2018, Damien et al. [33] examined the effectiveness of wooden enclosure walls with BPCM in two timber houses measuring 2.5 meters by 2 meters and 3 meters each at LAVAL University in Quebec, Canada. In winter, the electrical energy required for heating decreased. As temperature increased, wall enclosures were more effective at heating the cabin. In May, wall enclosures collected solar energy during the day, reducing the electrical energy required for heating the cabin by up to 41%.

In 2019, Mathis et al. [34] used three distinct versions of BPCM to produce visually appealing wood panels that consisted of a mixture of capric acid (CA) and lauric acid (LA), along with two classical formulas called PT20 and PT23. Analysis of DSC and DHFMA results was performed to elucidate the outcomes obtained by both methodologies. The wood panel made from the PT23 formula exhibits the highest energy storage capacity (57.15 J/g). On the other hand, the latent heat of fusion remained constant at all test times.

In 2022, Wu et al. [35] proposed a building envelope layer that included PCM and bio-based hygroscopic compounds. To study the effect of using PCM and PCM layer location on building energy efficiency, tests were conducted on four distinct envelope configurations. Each configuration depended on the presence of the PCM and its location within the envelope. When the PCM layer was placed in the center of the envelopes and left partially melted, the amplitudes of relative humidity and temperature decreased by 50 to 60%. Additionally, energy consumption was reduced by 15.3% compared with the configuration without PCM, and the maximum temperature decreased by 74%. Structures with BPCM on the outer layer exhibited greater energy efficiency, absorbed the most heat, and were prone to overheating and melting.

The experiments were conducted by Roberto and Piero [36] in 2023 on varying positions of hardwood wall enclosure with BPCM using the mixture of inorganic hydrated salts. The results showed that using a single internal enclosure led to a significant drop in cycle-dependent thermal conductivity from 0.147 W/m2 K to 0.092 W/m2 K, a reduction factor of 0.032, and an additional 2-hour increase in time lag compared with the control structure without PCM. Adding enclosure structures on both sides of the specimen increased the time lag by 1.6 hours; however, it reduced cycle-dependent thermal conductivity to 0.087 W/m2 K. The reduction factor increased to 0.049 due to the solidification and melting processes of BPCM, thus affecting the specimen surface temperature.

In 2024, Guermat et al. [37] reported on using of local vegetable oils and beeswax as BPCM to build walls and store energy. The results indicated that incorporating BPCM significantly increased energy storage capacity. The PCM reduced the maximum inner surface temperature by 3.95 °C, 3.25 °C, 3.17 °C, and 2.98 °C for the cities of Bachar, Tamanrasset, Constantine, and Annaba, respectively.

2.1. Thermal energy storage applications

In 2014, Hu and Yu [38] developed a BPCM by encapsulation of organic soybean wax within nanofibers-polyurethane by employing a method known as coaxial electrospinning. The results indicated that coaxial electrospinning could generate fibers with a homogeneous morphology, an interior shell structure, and uniform wax dispersion throughout the fiber core. The use of soy-based wax did not yield positive results regarding compatibility with the nanofibers-polyurethane mixture. Thermal analysis results show that increasing the amount of added wax increases the enthalpy values. No changes in thermal properties were observed throughout the cooling and heating cycles. Thus, the nanofiber mixture is thermally stable and reliable. Moreover, tensile testing demonstrated that the addition of soy wax improved elasticity indicators but reduced tensile strength.

Soroush et al. [39] carried out a study in 2018 regarding the melting behavior of nanoparticles with BPCM in a hollow cylinder system. The experimental setup includes the uniform heat bath and two vertical cylindrical structures. The first one was made from pure BPCM, which is produced using coconut oil, while the second one included CuO nanoparticles in BPCM. The pure BPCM and the nanoparticle with BPCM react in the same way during the initial stage of the melting process. However, when heated continuously, the nanoparticle-BPCM melts in less time than the neat BPCM, as can be seen in Figure 5.

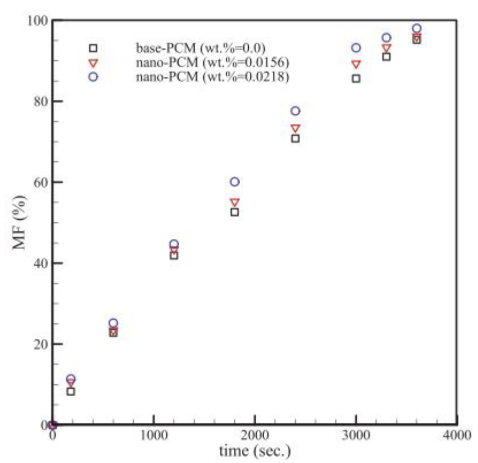

Figure 5. Variation in melting fraction of BPCM (wt.% =0) and Nano-BPCM (wt.% =0.0156 and 0.0218) [39]

Bence et al. [40] in 2018 employed a technique of recurring interface cross-linking and coacervation in order to create sustainable and eco-friendly heat storage microcapsules containing organic coconut oil as the BPCM. Although the technique was developed for paraffin wax, it worked well for producing a high BPCM quantity (81.1%) in coconut oil. The resulting microcapsules were spherical, exhibited a core-shell structure with a thermally stable calcium alginate shell, biocompatible, and scalable for industrial applications, as illustrated in Figure 6. Differential scanning calorimetry (DSC) was used to determine thermal properties such as melting point, crystallization temperature, heat capacity, and latent heat associated with phase transitions. In this method, a small sample was subjected to a controlled temperature program while the heat flow was monitored. The DSC analysis revealed that the melting and freezing enthalpy changes for pure coconut oil were 115.3 J/g and 108.1 J/g, respectively. In contrast, the corresponding heat storage capacities of calcium alginate microcapsules containing coconut oil were 84.7 J/g and 84.5 J/g, respectively.

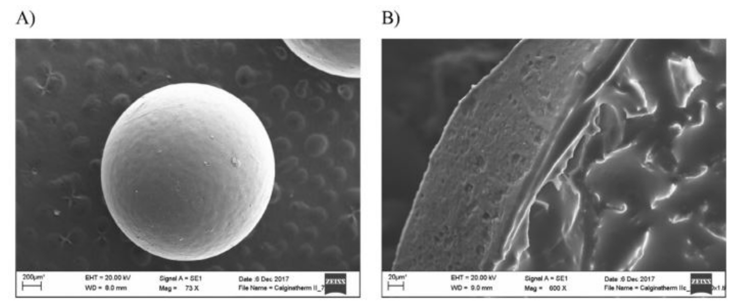

Figure 6. SEM images of calcium alginate microcapsule **(A)** containing coconut oil, **(B)** its cross-section [40].

In 2019, Rudramurthy et al. [41] investigated the temperature and the volume specifications of BPCM named OM55, derived from combinations of organic fatty acids. OM55 exhibited significantly higher thermal conductivity than commercial paraffin wax, which is often used in solar water heaters. Evaluations of temperature variations, enthalpy, and specific heat were found to be reasonably precise. The study revealed that OM55 could be used as a BPCM in various thermal applications.

In 2019, Lua et al. [42] blended the bio poly lactic acid (PLA) and high-density polyethylene (HDPE) for TES applications as a BPCM, with PLA serving as the supporting to create new stabilize shape. The results indicated that no chemical reaction occurred between PLA and HDPE during the melting process. However, the addition of PLA reduced the crystalline regions of HDPE. The latent heat capacity of the combination of 50% PLA and 50% HDPE was 100.1 J/g during the melting process and 97.6 J/g during the freezing process.

In 2019, Rasta and Suamir [43] investigated water-oil ester as a BPCM. The BPCM was tested using PCM based on salt with propylene glycol (PEG) as solvent. The results indicated that combining BPCMs with the appropriate amount of vegetable oil ester could lower the freezing temperatures and reduce or eliminate supercooling of water. PCMs based on salt and PEG exhibit excellent supercooling capacity and low latent heat storage. This study found that these BPCMs are effective for TES at subzero temperatures.

In 2020, Claudia et al. [44] investigated the potential of using outdated palm oils from the food industry as an environmentally friendly alternative to petroleum-based PCMs. DSC results showed two distinct phase-change temperatures, with a phase-change enthalpy of approximately 50 kJ/kg, as shown in Figure 7. Based on the results of the kinetic investigation, the two-dimensional phase-boundary reaction model was identified as the best model to describe palm oil oxidation.

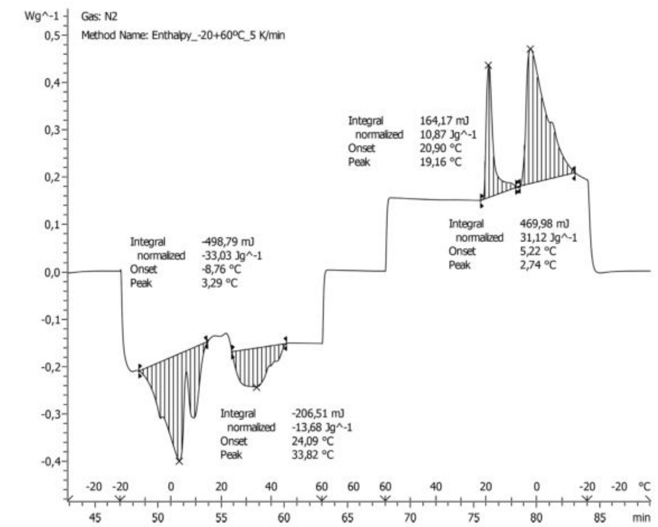

Figure 7. DSC results of outdated palm oil [44]

In 2020, Murthy and Gumtapure [45] identified shellac wax as a unique BPCM. The shellac wax comprises various functional groups, such as aliphatic hydrocarbons, carboxylic acids, esters, and alcohols. The temperature stability and chemical composition of Shellac wax were determined using TGA (thermogravimetric analysis), which measures weight variation as the material is heated under controlled conditions. The TGA test showed that the BPCM had no weight variation during its operation, between 50oC and 85oC. The crystallization and melting enthalpies obtained from the DSC analysis were 161 and 148 Kj/kg, respectively. The thermal parameters for the specimen remained consistent over 300 heat cycles. Furthermore, parameters such as thermal conductivity, specific heat, viscosity, and density of the material are similar to those of traditional PCM used in the storage unit.

In 2020, Sam et al. [46] found the melting points of one type of BPCM and three types of paraffin-based PCMs to be 24°C, 25°C, and 26°C, respectively. Using DSC analysis, the thermal energy storage capacity, phase-change behavior, and latent heat enthalpy of the material were evaluated. The outcomes indicate that BPCMs and paraffin-based PCMs have comparable TES capabilities across the set of phase-change temperatures representing human comfort.

In 2021, Meysam et al. [47] developed a stable formulation of BPCM through incorporating various quantities of the oleic acid (OA) and the linoleic acid (LiA) with the fatty acids of coconut oil (COFA). According to T-history and DSC studies, the melting temperatures of the BPCMs were estimated to be between 18°C and 25°C. Notably, the melting behavior was consistent, and the BPCMs exhibited supercooling of less than 0.6 °C.

In 202, Liu et al. [48] created biological shape-stabilized composite PCMs through combining paraffin wax(PW),chemically treated wood(CTW)as the porous matrix, myristic acid(MA),and poly-ethyl glycol(PEG).The chemical treatment removes both lignin and hemicellulose from the wood, thereby reducing its density and increasing the PCM absorption. PW/CTW, MA/CTW, and PEG/CTW exhibited latent heats of approximately 181.9, 179.1, and 132.6 J/g, respectively. The final product obtained after 1000 heating–cooling cycles exhibited superior thermal-management capability and stability compared with both PEG/CTW and PW/CTW.

The novel epoxy material referred to as DGEM has been developed by Liu et al. [49] in 2022. It consists of FA and MA, which are bio-sourced. These materials formed a cross-linked, reversible network through epoxy-amine ring opening and Diels–Alder (DA) reactions. Furthermore, phase-change characteristics were added to this supporting structure by combining 1-Octadecane-thiol (ODT) with the magnolol C=C via a "thiol/ene" reaction and by adding beeswax (BW). The results showed that the DA reactions could occur at temperature ranges less than 80 °C, allowing the cross-linked structure to be regenerated. The inclusion of BW and ODT in the 18DGEM/MA/FA/1.1BW sample contributes 119.15 J/g to the latent heat of fusion.

The effect of free convection on both the melting front and solidification front that happened during charging and discharging in a vertical shell and tube in 2022 has been studied by Murthy et al. [50] using BPCM made of shellac wax and Therminol R55 heat transfer fluid (HTF). Use of HTF resulted in a reduction in melting time of up to 43.6% at an average flow rate of 4L/min, whereas storage capacity and melting time were reduced by 73.4% and 42.2%, respectively. However, an increase in flow rate during the release process had no effect on solidification and discharge performance.

Jahangir et al. [51] used a fatty acid ester from an organic source as a BPCM in a greenhouse setting in 2022, which plays a crucial role in the production process of agriculture. Based on an energy-savings analysis, BPCM can save up to 14,577 kWh of energy per year in greenhouses. In addition to electricity, the use of BPCM in greenhouses can significantly reduce gas consumption during winter, thereby reducing gas energy consumption by 1348 kWh annually. Considering the environment, the maximum annual carbon reduction is 6.2 tons; this can be increased to 8.6 tons.

Ong et al. [52] analyzed the chemical composition and thermophysical properties of coffee oil to evaluate the effectiveness of using coffee oil as a BPCM in 2023. According to DSC results, the melting point of coffee oil is approximately 4.5 oC, while the latent heat of the coffee oil is 51.15 J/g. The gas chromatography-mass spectrometry analysis revealed that fatty acids constitute 60–80% of coffee oil. The FTIR and DSC results demonstrated the high chemical and thermal stability of coffee oil obtained by thermal cycling. An experimental study showed that coffee oil can maintain low temperatures for up to 46 minutes, suggesting that it can be used as a method of cold treatment.

The application of ecospheres for having an economic form of BPCM made from vegetable oil was studied by Ismail et al. [53] in 2023.The ecospheres were chemically etched to create gaps through which molten BPCM was poured to form BPCM microcapsules. Then, BPCM leaks were sealed with silica to prevent leakage from the capsules. The capsules exhibited improved thermal stability and conductivity and showed no leaks. The silica coating reduced the heat degradation of BPCM by about 16°C. When 10% of the sand was substituted with silica-coated BPCM, compression effectiveness improved. The best ratio for compressive strength was found to be a 20-30% substitution of sand with chemosphere microcapsules. However, due to the aqueous characteristics of the silica coating, the flexibility of the blend containing silica-coated BPCM decreased when the substitution percentage exceeded 30 % by volume.

The thermal properties of BPCM synthesized from hydrolysis of palm oils by utilizing MAGs as a solvent were analyzed by Manisara et al. [54] in 2023. The study found that increasing MAGs increased both the maximum and minimum melting points of the BPCM. Consequently, the upward change and widening of the maximum absorption, facilitated by MAG-emulsifying of BPCM, can lead to an increase in the operating temperature. The improved degradations and thermal specifications of the BPCM—associated with the molecular reactions between derivatives of palm oils (alkanes (ALKs) and MAGs)—are shown by differences between molecular simulations (paraffin) and the thermal characteristics decided by the DSC. The higher levels of crystallization in the BPCM blend and the decline in its melting point following the second heating were attributed to stronger MAGs-MAGs and ALKs-ALKs interactions than to ALKs-MAGs interactions. These findings provide considerable insight into possible emulsion-based processes for controlling the operating temperature.

A palm fatty acid distillate (PFAD) was utilized as a BPCM in 2023 by Abdulmunem et al. [55], and the effects were analyzed in terms of the thermal management and the power generated by lithium-ion batteries (LIB) at three different discharging loads, which are 50 W, 100 W, and 150 W. The use of PFAD reduced the operating temperature of the LIB by 9.8%, 19.5%, and 12.4%, while increasing the cell's electrical power by 17%, 20%, and 43%.

Yadav et al. [56] prepared eco-friendly nanostructures of carbon derived from Prosopis juliflora (PJ) in 2024, then reduced the sizes of the nanoparticles through ball milling. Nano-inclusions were then dispersed in PEG-1000. The composite reached its maximum thermal conductivity of 0.49 W/mK at 0.7 wt.% of 3-D (PJ) biochar. In addition, the melting point of the PEG-PJ compounds remained within the range of 40.1-40.5°C. Moreover, the latent heat values for these compounds increased markedly, ranging from 145 J/g to 152.7 J/g.

In another investigation in 2024, Yadav et al. [57] integrated BPCM with microparticles made from wheat husk (WH) as TES materials. The size of the WH particle was reduced by ball milling. Additionally, composites were prepared using a two-step ultrasound process to disperse the WH microparticles. The results indicated that the addition of 1.0 wt.% bio-based WH microparticles increased the thermal conductivity by 103% compared with the base BPCM. Furthermore, after conducting 500 heat cycles, the resulting composites were found to be thermally stable with only minor changes in their thermophysical parameters.

Though the earlier part focused on the benefits and applications of BPCMs based on organic materials, this part focuses on BPCMs based on composite materials, which combine multiple materials to improve thermal properties and sustainability.

2.2. Composite-based BPCMs

To overcome the drawbacks of various types of PCMs, BPCMs combine organic and inorganic substances in composite form. It uses good thermal energy storage capacity and high thermal conductivity of organic-based BPCMs. However, optimizing the dispersion and stability of these components in the composite structure can be challenging. The organic and inorganic materials explored as PCMs include fatty acids, polyethylene glycol (PEG), and paraffin wax. The building industry can routinely manage interior temperature changes by combining these materials into construction components. Most of these PCM integration approaches focused on absorbing and releasing thermal energy for interior heating. The following review explores composite BPCMs suitable for various applications.

2.3. Thermal energy management applications in buildings

In 2014, Su-Gwang et al. [58] prepared composite materials using BPCM with porous nitride of boron utilizing the vacuum-impregnation procedure to solve the leakage and poor thermal conductivity concerns of bio-based PCMs. The results showed that composite BPCM exhibited a 477% increase in thermal conductivity compared with the pure bio-based PCM. This shows that boron nitride enhances the thermal conductivity of bio-based PCM. Thermal conductivity analysis indicates that the developed composite BPCM is suitable for various TES applications, such as the building sector.

In 2015, Kang et al. [59] developed a BPCM using vacuum-impregnating silica fume with bio-based materials. Silica fume, a mineral admixture, is a promising low-cost, lightweight TES material for use in the construction sector. Including exfoliated graphite nanoplatelets (xGnP) is another strategy to improve the thermal conductivity of the PCM. The addition of silica fume and xGnP improved the thermal conductivity of the BPCM. The BPCM with silica fume increased by 156% relative to the PCM, whereas the composite with xGnP increased by 243%.

In 2019, Yoo et al. [60] produced BPCM composites by incorporating spent coffee (SC) wastes as bio-wastes into different organic waxes such as beeswax (BW), palm wax (PW), golden soy wax (GW), and nature soy wax (NW). The findings showed that the coffee waste was vacuum-impregnated into all organic waxes, resulting in high thermal performance and stability. Figure 8 shows the DSC findings for the composites SC/BW, SC/PW, SCG/W, and SC/NW. Compared with existing BPCMs, the newly developed composite BPCMs exhibit adequate thermal characteristics for building applications.

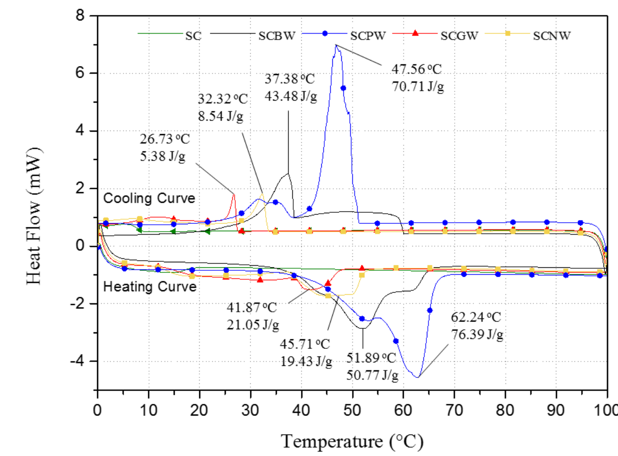

Figure 8. DSC curves of BPCM composites [60]

In 2021, the hydrothermal behavior of a layered building envelope made up of a polycarbonate membrane and hemp lime concrete (HLC) was investigated by Wu et al. [61]. Four envelope arrangements were used to investigate the effect of PCMs and the location of PCMs on the envelope's hydro-thermal performance: one without PCM and three with PCM (PCM placed on the interior side, the exterior side, and the center of the envelope). The results showed that PCMs significantly influenced the hydrothermal performance of HLC. The enhancement of heat storage and release performance by the PCM varied linearly with its location. The closer the PCM was to the exterior, the greater the heat storage and release performance and the lower heating and cooling load from the envelope to the interior space.

Micro-encapsulated BPCM was developed by Parameshwaran et al. [62], which was incorporated into the micro-concrete composite BPCM in 2021. The micro-encapsulated BPCM exhibited continuous phase-change behavior and a latent heat capacity of 47.31 J/g. In addition, permeability and thermogravimetric analyses indicated that the micro-encapsulated BPCM was thermally stable between 35 and 150 oC. The fabricated micro-concrete composite BPCM was found to be structurally stable, with a compressive strength of 38.78 MPa at a micro-encapsulated BPCM content of 0.075% of the cementitious material.

Lin et al. [63] produced metallic wood-based phase change materials (MWPCM) in 2022, by impregnating wood with phase change microcapsules PCM followed by performing in situ chemical deposition of copper within the wood cell lumen. A polymer encapsulates PCM, forming phase-change microcapsules that successfully alleviate leakage problems. The results demonstrate that MWPCM enhanced its longitudinal and radial thermal conductivities by 211% and 362%, respectively, compared with net wood. The anisotropic thermal conductivity of MWPCM facilitated efficient longitudinal heat transfer while exhibiting low transverse thermal conductivity. The TES properties of MWPCM are considerable, with values of approximately 92.9 J/g and 94.6 J/g, and an appropriate phase-change temperature range of 11.4 °C to 29.4 °C, enabling regulation of internal thermal energy.

In 2022, Wu et al. [64] designed a passive enclosure that combines PCM and hemp cement for the improvement of energy, heat, and moisture management in the building. Compared with the first case without PCM, the results obtained with the PCM located close to the building's inner side showed considerable improvements. Such improvements corresponded to a decrease in heating load of around 8.2%, a temperature change of 46.3%, and a moisture pressure change of 43.7%.

In 2022, Sudipta et al. [65] produced a BPCM microcapsules with the chemosphere as the protective shell and a bio-inspired dopamine encapsulating to improve the manufactured cement mortar in the building's sector. Adding 10 wt.% of the BPCM microcapsule to the cement mortar resulted in a 35% increase in the mortar's compressive strength. Microstructural inspection and analysis of hydration products demonstrated that dopamine encapsulation accelerates cement hydration and results in a stronger, denser interaction between the cement paste and microcapsules.

The study of Nazari et al. [66] concerning the application of ethyl-palmitate (EP) as BPCM alongside wood particles in constructing applications was done in 2023. Combining the non-treated fiber with EP improved absorption capacity and fluidity. Over 99% of the biological substances used in the composition of the TES implementations consisted of an optimal blend of wood particles and EP, including 37.5% linseed oil. The composition with the best ratios was found to contain 25% BPCM. The combination of BPCM enhanced moisture inhibition by 2.07 g/m2 RH%.

Kehli et al. [67] investigated the barley straws treated with hot water employed in the lightened gypsum composite (BS.HW) and palm oil (PO) as BPCM in 2023. The results showed that the thermal diffusivity of the innovative lightened gypsum composite with a ratio of 1% BS.HW to 2.6% PO was 12.1% lower than that of the basic composition.

In 2023, Alipour et al. [68] investigated the thermal properties of a set of binary combinations of decanoic acid (DA) and methyl palmitate (MP) as BPCMs in 2023. Results revealed that the binary eutectic combination of 70% DA and 30% MP is a BPCM with favorable properties for use as TES in the building sector. These features include the melting and freezing temperatures of 20.19 °C and 15.08 WC, also good latent heat values of 201.43 J/g and 202.3 J/g, respectively.

2.4. Thermal energy storage applications

In 2014, Yu et al. [69] developed a BPCM by incorporating carbon-based nanomaterials which included exfoliated graphite nanoplatelets (xGnP) and carbon nanotubes (CNT)at mass fractions of 1.0, 3.0, and 5.0 wt.% into liquid BPCM to increase thermal conductivity. The results revealed good dispersion of the generated carbon nanomaterials within the BPCM composites and compatibility between these nanomaterials and the BPCM. As the added quantities of carbon nanomaterials increased, the thermal conductivities of the composites increased correspondingly (Figure 9). The DSC results confirmed that BPCM/xGnP maintain high latent heat values and acceptable phase-change temperatures due to their large surface area and the high dispersion of carbon-based nanomaterials.

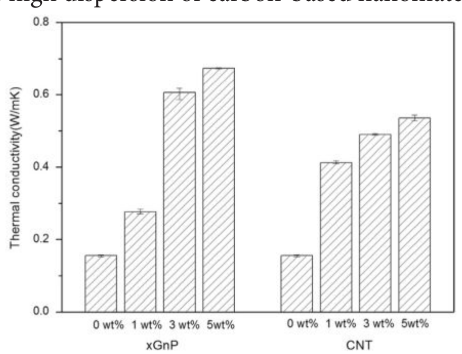

Figure 9. Thermal conductivity of the composite BPCM with xGnP and CNT additives [69]

In 2019, Al-Jethelah et al. [70] investigated the melting characteristics of coconut oil as a BPCM having copper oxide (CuO) nanoparticles inside an aluminum metal foam and treated to a continuous heat flow boundary. Based on the results, using nanoparticles with metallic foam increased both the energy storage rate and the melting temperature. The results also showed that homogeneous melting could occur in porous materials with a low porosity of 88%. The incorporation of nanoparticles into the BPCM enhanced its melting rate by 1.2%; however, incorporating metallic foam into the BPCM produced a significant improvement in the melting process.

In 2019, Lua et al. [71] produced a BPCM for TES by combining polyurethane (PU) and wood powder (WP). They investigated the thermal and crystalline properties, chemical composition, and structure of this composite material. Despite having only 3.0 wt.% WP, the BPCM demonstrated exceptional thermal stability and phase-change behavior throughout the solid-liquid phase-change region. BPCM has peak latent heats of solidification and melting of 132.4 J/g and 134.2 J/g, respectively, with an enthalpy efficiency of 98.7%. Simultaneously, the produced BPCM demonstrated consistent light-to-thermal conversion and temperature-regulation capabilities.

In 2019, Liang et al. [72] employed vacuum adsorption to produce bio-based polyethylene glycol (PEG)/wood flour (WF) composites as a BPCM. The relationships between structure and overall effectiveness of the BPCM were developed by varying the average molecular masses of PEG and the length-to-diameter ratios of WF. Based on the results, no specific physical interaction between PEG and WF was observed, and the degree of PEG crystallization in the BPCM composite decreased. Furthermore, DSC analysis demonstrated that the melting point was not related to the quantity of WF supplied or to the length-to-diameter ratio.

In 2020, Liu et al. [73] synthesized BPCM using polyethylene glycol (PEG)in position filled with Ca^{2+} cross-linked sodium alginate (SA) because Ca^{2+} is coordinated with carboxyl groups that exist in the SA structures. The PEG/SA composites had a PEG loading of 93%, and the phase-change enthalpy could reach 156.8 J/g. These materials also exhibit good form stability and outstanding heat-management properties. As a result of its biological compatibility, non-toxicity, and high latent heat, it holds significant promise for use in medical thermal insulation applications.

In 2020, Sheng et al. [74] investigated on using pomelo peel foam (PPF) with PEG as a new BPCM by the process of simple impregnation. They added small quantities of MXene nanosheets to increase its thermal conductivity, thermal energy storage capacity, and light-to-heat conversion efficiency. The incorporation of MXene nanosheets into PPF significantly improved the light-to-heat conversion efficiency. The incorporation of PEG into form-stable composite PCMs rose from 86.9 wt.% to 96.2 wt.%, resulting in an increase in thermal conductivity from 0.25 to 0.42 W/mK.

Hu et al. [75] produced a BPCM using reduced graphene oxide (RGO) with spent coffee grounds (SCGs) in 2021. SCGs of 1–5 wt.% and RGO were used as support structures to keep the shape of the BPCM and to address concerns about leakage and low light-to-heat conversion efficiency. RGO-modified SCGs (SCGs@RGO) exhibit a more developed 3-D porous structure than that of pure SCGs and can absorb 60.3 wt% of polyethylene glycol. Furthermore, they have excellent leakage resistance and show slight improvements in thermal conductivity. The SCGs/RGO composite has an extremely high capacity for light-to-heat conversion and retains solar heat during a short illumination period of about 244 seconds due to its strong absorption across the entire UV/Vis/NIR wavelength range.

The thermal properties of the BPCM based on composites as a heat sink were evaluated by Sheikh et al. [76] in 2022. They used 3 CFM samples with pore densities of 35, 80, and 95 PPI, and 3 independent filled-height ratios of 1.0, 1.3, and 1.6. The results revealed that the best cooling performance was achieved by a BPCM/CFM with a pore density of 95 PPI, which exhibited improvement ratios of 1.44 and 1.54 under thermal loads of 15 W and 10 W, respectively.

Suqing et al. [77] used photo-deposition and hydrothermal methods to manufacture photothermal catalysts, Au/TiO_2 in 2022. Microcapsules combining PCM and these catalysts were produced via electrostatic adsorption and self-assembly to enhance solar energy conversion and storage performance across the solar spectrum.

The Au/TiO_2 shells incorporation ratios for the microcapsules were 12.7% and 15.5%, respectively, for rod and sheet-shaped samples. The results showed that the average light-to-hydrogen efficiencies reached 11.4% and 5.0% for ATR/PCM and ATF/PCM, respectively, being increases of 53.8% and 56.1% over their equivalent catalyst nanoparticle suspensions. The composite PCM developed in this study exhibited dual functionality: energy storage and photothermal catalysis.

In 2022, Xiao et al. [78] used a chemical reduction procedure to produce loofah-based porous carbon (BPC) with Nano-Ag particles added. The product was a novel PEG/BPC-Ag shape-stable composite PCM. Results showed that the PEG/BPC-Ag BPCM photothermal conversion effectiveness increased from 76.7% to 92.2% after incorporation of Ag nanoparticles, and the BPCM's thermal conductivity increased from 0.349 W/mK to 0.632 W/mK. Positive melting behavior remained apparent after 100 heat cycles, confirming the thermal reusability and stability of PEG/BPC-Ag. The results indicated that PEG/BPC-Ag could be useful for various applications, especially photothermal energy conversion and TES systems.

In 2023, Du et al. [79] designed a flexible composite PCM (FCPCM) that performed well in terms of efficiency and innovation by incorporating PEG in the sandwich-shaped composite foam (SCF) consisting of melamine foam (MF) and bacterial-based cellulose (BC). Both MF and BC have produced SCF with multiple pore structures and high resistance to leakage. The FCPCM with a 0.999 storage capacity was developed using the vacuum impregnation method with PEG. After 100 heating cycles, the composite materials exhibited high thermal stability.

The synthesis of BPCM using polyurethane (PU) and polylactic acid (PLA) by Li et al. [80] in 2023 demonstrated a high recycling ability and good form stability for TES. Experiments reveal that the addition of PLA improves the leak-free performance and mechanical strength of the PLA/PU composite. When the PLA component was 20% or 40% of the PLA/PU composite mixture, the relative enthalpy efficiencies were 79.14% and 91.51% of the original, respectively, which benefited TES function. The foregoing results suggest that PLA/PU composites are an efficient solution for applying green technology in the field of TES.

In 2023, Alipour et al. [81] investigated the thermal properties of a variety of binary mixtures of methyl palmitate (MP) and decanoic acid (DA) as a BPCM. Based on the results, a eutectic mixture of 70% DA and 30% MP work best BPCM as a TES in building sector and has 201.43 J/g and 202.3 J/g of latent heat of melting and freezing, and 20.19 °C and 15.08 °C of realistic melting and freezing temperatures.

Huang et al. [82] developed a BPCM by mixing biomass cellulose nanocrystals (CNCs)in 2023, konjac glucomannan (KGM), MXene (a two-dimensional material), and $AgNO_3$ in a simple and fast physical process before subjecting them to directional freeze-drying and thermal annealing process. The BPCM was formed by impregnating paraffin into lightweight porous carbon aerogels. BPCM's features included a high loading of 95.16%, a high enthalpy of 231.38 J/g, an exceptional conductivity of 147.5 S/m, and high cycle stability. Furthermore, PMCKA can attain efficiencies for electro-thermal and photo-thermal energy conversions of more than 98.9% and 97.5%, respectively.

Masoud et al. [83] developed in 2023a composite BPCM consisting of beeswax and oleic acid that has been incorporated with metal matrix sheets (MMS) to absorb heat energy from the PV panels. The findings show that using the BPCM technology decreases the variation in PV panel temperatures from 58.92 oC to 51.45 oC, and that the application of MMS further decreases PV temperatures compared with PV panels operating with PCM alone, thereby enhancing electrical performance.

BPCM was developed by Sheng et al. [84] in 2023 through the use of wood flour (WF), PEG, and polylactic acid (PLA). Investigation of the combination of PEG and WF (WP) showed that WF effectively retained PEG owing to capillary action. WP combined with a PLA compound (WPC) retained an adequate latent heat of fusion of 87.3 J/g. The use of WP conferred enhanced properties on PLA across a wide range of temperatures.

McCord et al. [85] used decanoic acid (DA), and palmitic acid (PA), in bio-based samples manufactured from sodium alginate (SA) and flax fiber (FF) as a composite BPCM in 2024. In addition, a conductive polypyrene (PPy) coating was synthesized via in situ polymerization to fabricate two thermal energy storage and conversion devices with different phase-transition temperatures. However, the PPy film was homogeneous and exhibited a thermal conductivity of 0.453 W/mK. The mixed BPCM material was permeable, with a porosity of 85%. This facilitated the immobilization of 60% and 74% of DA and PA, respectively, resulting in improved energy-storage and energy-conversion properties. Phase transition enthalpies of the mixed BPCM containing DA and PA were 100.98 and 154.52 J/g, respectively.

Mert et al. [86] developed a new type of compound BPCM in 2024 by using fatty acid BPCM, where oleic acid (OA) acted as BPCM and emulsion template microporous polymers as support materials. Furthermore, microporous support materials were synthesized as surface-modified montmorillonite nanoclay. Based on DSC results, the produced composite PCMs are suitable for cold thermal energy storage applications, such as building cooling, cold protection, and cold-chain transportation, due to their appropriate melting points (7.08 °C and 7.40 °C) and moderate latent heat capacities.

3. Summarizing of the literature survey

Table 1 below presents a summary of the studies discussed in the literature review, emphasizing methods of preparation, applications, and results achieved by BPCMs in various TES systems.

Table 1. Summaries of the studies presented in the literature survey

A. Organic BPCMs

- **Thermal energy management applications in buildings**

Authors [Ref.], Year	Materials used to form BPCM	Preparation method	Important results
Boussaba et al.[22], 2018	Coconut fat combined with a composite matrix made of natural clay and cellulose fibers	BPCM is included in a composite matrix using the direct immersion approach.	• Increasing the thermal inertia of building envelopes and the composite BPCM was also chemically stable.
Boussaba et al.[23], 2019	hydrogenated palm kernel oil with composites of cellulose fibers and natural clay	BPCM is included in a composite matrix using the direct immersion approach.	• Adding graphite enhanced the heat conductivity of this material and was chemically stable.
Hekimoglu et al. [24], 2021.	WSC (walnut-shell carbons) and AWSC (activated walnut-shell carbons) with MP (methyl-palmitate)	Carbonization and chemical activation of walnut shell (WS) resulted in the production of two types of bio-carbons that are lightweight, porous, low-cost, and environmentally benign.	• Under technique of the chemically activation, the of WS's pores size and surface area increased by 1.44 and 1.47 times. • The melting temperatures of AWSC/MP and WSC/MP were 26.65 °C and 26.27 °C. • The AWSC/MP and WSC/MP exhibited thermal conductivity values around 1.58 and 1.9 times higher than the used MP.
Zhao et al.[25], 2022	Polyethylene glycol (PEG)/ organic diatomite (O-Dt) and wood fiber (WF)/high-density polyethylene (HDPE) as the supporting structure.	PEG was embedded in the porous structure of O-Dt.	• The BPCM demonstrated a considerable thermal storing capacity about 60.42 J/g, and temperature regulation between 12-15 °C. • Comparative to 0% BPCM, the thermal conductivity of 20% BPCM increased by 26.7%. In addition, 5% BPCM was loaded into supporting structure, both their strength and hydrophilic properties were increased.
Naresh et al.[26],2022	Fly ash (FA) stones with acid of n-dodecanoic.	Vacuum impregnation method.	• Leak stability at 85 °C and thermal stability at 150 °C. • After undergoing a thorough temperature testing process of 1000 cycles, the BSPCM demonstrated an impressive thermal reliability rate of 96.76%.
Naresh et al.[27],2022	Hexadecanol with fly ash (FA) stones.	Vacuum impregnation method.	• After 1000 melting and freezing cycles, the thermal stability of the BSPCM is good, with a fusion enthalpy of 114.41 kJ/kg. • Leak stability above 85 °C, which is a higher temperature than the PCM's working temperature. • The BPCM has a 0.3397 W/m K of thermal conductivity value; make it suitable for banning heat solar energy from entering a building structure.
Choi et al. [28],2022.	PCM with coffee wastes	Blending microencapsulated PCM (MPCM) with coffee waste.	• Increasing MPCM ratios lead to the temperature decreases more slowly because MPCM retains heat over time. • MPCM had a better sound absorption coefficient and increased acoustic performance
Biswas and Abhari [29], 2014	Glycerides, fatty acids in the high-density polyethylene, and cellulose	Adding glycerides and fatty acids to cellulose.	• Reduced power consumption of the building cooling system.
Cellat et al.[30], 2015	Myristic acid (MA), capric acid (CA), palmitic acid (PA), and lauric acid (LA)	BPCMs are included into concrete.	• Chemical and thermal stability. • The compression strengths of concrete mixtures containing 1 wt% BPCM were reduced by 12%. • Increased BPCM levels to 2 wt% lead to compression strengths falling even more.
Tor et al.[31], 2017	Fatty ester	Fatty esters are integrated into the ceiling, floor, and walls.	• Provide a significant quantity of cooling load.
Yassine et al.[32], 2017	Bio boards named IBS IZOLOX with BPCM.	BPCM is combined with inner wall layers.	• Increase the comfortable thermal effectiveness of the building throughout the winter season.
Damien et al.[33], 2018	Wooden wallboards with BPCM.	BPCM has been integrated into wood-based panels.	• The quantity of energy consumed for heating decreased. • Save up to 41% of the power required for heating.

Authors [Ref.], Year	Materials used to form BPCM	Preparation method	Important results
Mathis et al.[34], 2019	Lauric (LA) acids and capric (CA), with two conventional formulations dubbed PT20 and PT23 to make wooden panels.	Incorporating a BPCMs combination onto wood panels.	• The panel made with PT23 had the most energy storage, measured at 57.1 J/g.
Wu et al.[35], 2022	PCM and bio-based hygroscopic compounds.	PCM and hemp concrete combine to form a multilayer envelope.	• When the PCM was placed in the center of the envelopes and left partially melted, the amplitude of temperature/relative humidity decreased by 50 to 60%, the quantity of energy consumption decreased by 15.3% when compared to the configuration without including PCM, and the maximum temperature decreased by 74%. The PCM on the exterior side had the highest energy efficiency, absorbed the greatest amount of heat, and was also more prone to overheating and melting.
Roberto and Piero [36], 2023	Wooden wall envelopes with BPCM produced from a blend of inorganic hydrated salts.	Wooden wall envelopes integrated with BPCM	• Using just one envelope on the internal side, the cyclical thermal conductivity significantly decreased from 0.147 W/m^2 K to 0.092 W/ m^2 K, resulting in a decrement factor of 0.032, as well as a 2-hour increase in the lag of time compared to the base scenario without PCM. • When envelopes are applied on both sample sides, the time delay rises by 1.6 hours, and cyclical thermal conductivity is limited to 0.087 W/m^2 K. However, the decrement factor rose to 0.049 due to the processes of melting and solidification of the used BPCM affecting the sample's surface temperatures.
Guermat et al.[37], 2024	Vegetable oils and beeswax as BPCM	Integration of BPCM into building walls.	• Using BPCM considerably increases energy storage capacity and reduces the highest temperature of the building's inner surface.

- **Thermal energy storage applications**

Authors [Ref.], Year	Materials used to form BPCM	Preparation method	Important results
Hu and Yu [38], 2014	organic soy wax with polyurethane nanofibers	Coaxial electrospinning is used to encapsulate organic soy wax into polyurethane nanofibers.	• The concentration of wax present causes an increase in enthalpy value. • The combined fibers were thermally stable and reliable. • Tension tests showed that using the presence of soybean wax leads to an increase in the elasticity values, and decreases the values of tension strain. .
Soroush et al. [39], 2018	Coconut oil with CuO nanoparticles.	Bio-based nano-PCMs are used to fill cylindrical systems.	• CuO-BPCM additives at wt% = 0.1 and 1 increase by 4.8 % and 7.5 % in thermal conductivity, and reduce the latent heat of fusion by 1.94 and 8.25 % compared to the basic PCM at wt.
Bence et al.[40],2018	Microcapsules of calcium alginate containing coconut oil	Method of interfacial coacervation and crosslinking.	• The melting and freezing enthalpy changes were found to be 115.3 J/g and 108.1 J/g, respectively, for the pure coconut oil. The corresponding heat storage capacities of calcium alginate microcapsules containing coconut oil were 84.7 J/g and 84.5 J/g, respectively.
Rudramurthy and Gumtapure[41], 2019	Organic fatty acids (OM55).	Made from a combination of organic fatty acids.	• OM55 has a high thermal conductivity compared to commercial paraffin wax.
Lua et al.[42], 2019	Poly lactic acid(PLA) and high-density polyethylene (HDPE)	Combining PLA and HDPE to create shape-stabilized BPCM.	• The addition of the PLA material reduced the crystalline regions of HDPE. • The latent heat capacity of the 50% PLA with 50% HDPE combination is 100.1 J/g during its melting process and, 97.6 J/g during the freezing process.
Rasta and Suamir[43], 2019	Ester of vegetable oils with PCMs based on salt and PEG.	PCMs are combined with a vegetable oil ester.	• Combining PCMs with the appropriate amount of vegetable oil ester, can lower freezing temperatures and reduce or eliminate supercooling of water. • PCMs based on salt and PEG exhibit excellent supercooling capacity and low storage of latent heat.
Claudia et al.[44], 2020	Palm oils	Palm oil that has expired in the food sector.	• The thermal monitoring process and the DSC both showed two separate melting points. These ensure the enthalpy of melting of about 50 kJ/kg.

Murthy and Gumtapure [45],2020	Shellac wax	Use FTIR, TGA, and DSC to characterize the shellac wax.	• Shellac wax did not change mass when operated at temperatures ranging from 50 to 85 °C. • The sample's thermal properties did not change much during 300 heat cycles. • Specific heat, thermal conductivity, and viscosity density are comparable to those of conventional PCM used in storage systems.
Sam et al.[46], 2020	Three types of paraffin PCMs and one BPCM.	Characterize PCMs using two distinct methods: conventional dynamic DSC and a stepwise approach.	• The BPCMs and paraffinic-PCM had the equivalent TES capabilities.
Meysam et al.[47], 2021	Linoleic acid (LiA) and oleic acid (OA), and coconut oil fatty acids (COFA).	Combining LiA and OA in various quantities with COFA.	• The melting point of the BPCMs varied between 18 °C and 25 °C. • There wasn't a divergence in melting, and the BPCMs demonstrated below 0.6 °C of supercooling
Liu et al.[48], 2021	Chemically treated wood (CTW) and myristic acid (MA), paraffin wax (PW), and poly-ethyl glycol (PEG).	Vacuum impregnation method	• PW/CTW, MA/CTW, and PEG/CTW exhibited latent heats of up to 181.9 J/g, 179.1 J/g, and 132.6 J/g, respectively. • After 1000 heating-cooling cycles of the investigation, the resulting CTW has the best thermal management characteristics and thermal stability compared to PEG/CTW and PW/CTW.
Liu et al.[49],2022	BPCM (DGEM-18/FA/MA/xBW)	Bio C36-alkylenediamine bismaleimide (MA) and 2-furanmethanamine (FA) are used as fundamental components to create a cross-linked reversible network based on the epoxy-amine opening ring with Diels Alder (DA). Furthermore, phase change properties were given to this supporting structure by incorporating 1-Octadecane-thiol (ODT) into the magnolol C=C via a "thiol/ene" reaction, as well as beeswax (BW).	• BW and ODT in the 18DGEM/MA/FA/1.1BW sample add up to 119.15 J/g of the latent heat of fusion.
Murthy et al.[50],2022	Shellac wax with heat transfer fluid by Therminol R55 (HTF)	The BPCM has been included into the vertical shell and tube.	• Employing HTF decreased melting time by up to 43.6 % at an average flow rate of HTF by 4 L/min, where the efficiency of storage and the melting time are reduced by 73.4%, and 42.2% respectively. .
Jahangir et al.[51], 2022	Organic fatty acid ester	Organic fatty acid ester (BPCM) is being added to the greenhouse.	• Adding BPCM in greenhouses reduce up to 14,577 kWh of electrical power, and reduce natural gas energy use by up to 1348 kWh per year. In terms of environmental consequences, which lead to carbon reduction is 6.2 tons per year, which may be enhanced to 8.6 tons per year.
Ong et al.[52],2023	Coffee oil	Coffee oil was extracted and its characteristics were analyzed using DSC, GC-MS, FTIR, and DSC.	• Coffee oil had a melting temperature and latent heat around 4.5 °C and a 51.15 J/g, respectively. • Coffee oil extractions had exceptional thermal and chemical stability during heat cycling.
Ismail et al.[53], 2023	The ecospheres filled with refined edible vegetable oil.	The Cenospheres were etched chemically to produce the holes which were later filled using BPCM molten from vegetable oil and covered using silica in order to avoid leakage and increase thermal stability.	• Rising thermal stability and conductivity without leaks. The layer of silica slowed thermal deterioration of the BPCM by approximately 16 °C. • At 10% sand substitution with silica-coated BPCM, compression effectiveness was increased.
Manisara et al.[54], 2023	Monoacylglycerols (MAGs) and Palm oils.	BPCM was produced by hydrolyzing palm oil and emulsifying it with MAGs.	• Increasing MAGs boosts both the maximum and minimum melting points. As a result, the upward change and widening of the maximum absorption generated by MAG-emulsifying of BPCM can be raising the temperature at which it operated.

Abdulmunem et al.[55], 2023	Palm fatty acid distillate (PFAD)	PFAD is used as a heat sink for lithium-ion batteries.	• Applying PFAD reduced the operating temperatures of the LIB by 9.8%, 19.5%, and 12.4%, while simultaneously increasing the cell's electrical output by 17%, 20%, and 43%, for each applied load, respectively.
Yadav et al.[56], 2024	Nano-carbon with PEG-1000.	Carbon nanostructures from Prosopis juliflora were synthesized by ball milling and distributed as nano inclusions in PEG-1000.	• The composite reached its maximum thermal conductivity, 0.49 W/m·K, at 0.7 wt% of 3-D (PJ) biochar. • The melting point of the PEG-PJ composites varied between 40.1 and 40.5 °C. • Latent heat capacities increased noticeably, from 145 J/g to 152.7 J/g, representing a significant rise of 3.968% and 1.758%, respectively.
Yadav et al.[57], 2024	BPCM with microparticles made from wheat husk (WH)	Ball-milled wheat husk microparticles are dispersed into BPCM utilizing a two-step ultrasonic method.	• Adding bio-based 1.0 wt% WH microparticles increased heat conductivity by 103% compared to the basic BPCM. • The composites were shown to be thermally stable with minor changes in thermophysical parameters.

B. Composite BPCMs

- **Thermal energy management applications in buildings**

Authors [Ref.], Year	Materials used to form BPCM	Preparation methods	Important results
Su-Gwang et al.[58], 2014	Porous nitride of boron with BPCM	Vacuum impregnation method.	• The composite BPCM has a 477% increase in thermal conductivity, compared to the pure Bio-based PCM.
Kang et al.[59], 2015	Silica fume with BPCM and exfoliated graphite Nanoplatelets (xGnP).	The addition of xGnP to vacuum-impregnated silica fume via BPCM.	• The addition of silica fume and xGnP led to an improvement in the thermal conductivity of the BPCM. • The BPCM/silica fume increased by 156% relative to the PCM, but the rate of increase for the composite with xGnP was 243%.
Yoo et al.[60], 2019	Spent coffee (SC) with different BPCM like beeswax (BW), palm wax (PW), golden soy wax (GW), and nature soy wax (NW).	Adding vacuum-impregnated spent coffee waste to different waxes.	• High thermal performance and stability • The BPCMs have adequate thermal characteristics for building applications
Wu et al.[61],2021	Poly-carbonate membranes (PCMs) and hemp lime concrete (HLC)	PCMs incorporated HLC in various layouts (interior, exterior, and center of the envelope).	• PCM enhanced heat storage/release performance linearly with its location. • The closer the PCM was to the exterior, the greater the heat storage/release performance and lower heating and cooling load from the envelope to the interior space.
Parameswaran et al. [62], 2021	Microencapsulated bio-based phase change material (MbP) with a micro-concrete composite (MbPMC)	Microencapsulated bio-based PCM (BPCM) was developed and blended into a micro-concrete composite.	• The MbP showed consistent phase change behavior and an excellent latent heat potential of 47.31 J/g. • The MbP was thermally stable from 35 °C to 150 °C. • The MbPMC demonstrated satisfactory structure integrity with a compressive strength of 38.78 MPa at an MbP dosage of 0.075% of the weight of cementitious materials added to the blend.
Lin et al.[63], 2022	Microcapsules PCM and wood panels.	Wood is impregnated with PCM microcapsules, followed by in situ copper deposition inside the wood structure.	• MWPCM enhanced its longitudinal and radial thermal conductivity by 211% and 362%, respectively, as compared to net wood. • MWPCM has a high TES capacity of about 92.9 J/g and 94.6 J/g, and an appropriate temperature of phase change of 11.4 °C and 29.4 °C for interior heat energy management.
Wu et al.[64], 2022	PCM and hemp concrete.	Included PCM to hemp concrete.	• When the PCM was found near to the building's interior, the greatest improvements with decreases heating load, temperature fluctuation, and vapor pressure variations were about 8.2%, 46.3%, and 43.7%, respectively.
Sudipta et al [65], 2022	Microcapsule BPCM with the chemosphere.	BPCM microcapsules were developed by encapsulating chemosphere shells with dopamine.	• Adding 10 wt% of the BPCM microcapsule to the cement mortar resulted in a 35% improvement in the compressive strength of the mortar.

Nazari et al.[66], 2023	Ethyl-palmitate (EP) as a BPCM with particles of wood	Ethyl-palmitate (EP) was blended with untreated fibers and linseed oil.	• The composite BPCM had improved the levels of moisture prevention by 2.07 g/m^2 RH% and high thermal performance.
Kehli et al.[67], 2023	Barley straws and palm oil (PO) as BPCM.	The lightened gypsum composite (BS.HW) contained barley straws treated with hot water and palm oil (PO) as BPCM.	• The thermal diffusivity of the innovative composite of lightened gypsum with a ratio of 1% BS.HW to 2.6% PO is 12.1% lower than the basic composition.
Alipour et al.[68],2023	Methyl palmitate (MP) and decanoic acid (DA).	Eutectic BPCM is produced by combining binary DA with MP.	• The binary eutectic combination of 70% DA and 30% MP is a BPCM with favorable properties for application as TES for the buildings sector. • The melting and freezing temperatures of 20.19 °C and 15.08 °C, also good latent heat values of 201.43 J/g and 202.3 J/g, respectively.

- **Thermal energy storage applications**

Authors [Ref.], Year	Materials used to form BPCM	Preparation methods	Important results
Yu et al.[69], 2014	Graphite nanoplatelets (xGnP) and carbon nanotubes (CNT) with BPCM	Carbon-based nanoparticles are incorporated into BPCM.	• Good dispersion of additive materials into BPCM. • Increase the thermal conductivities of the composites BPCM with additive materials. • The BPCM/xGnP maintains high latent heat values and acceptable phase change temperatures due to their large surface area and high dispersion of carbon-based nanomaterials.
Al-Jethelah et al.[70], 2019	Coconut oil and copper oxide (CuO) nanoparticles.	Coconut oil was mixed with CuO nanoparticles and placed within an aluminum metal foam.	• Using nanoparticles with metallic foam increased the rates of energy storage and melting temperature. • Homogenous melting happend in porous materials with a low porosity of 88%. The incorporation of nanoparticles into the BPCM enhanced its melting rate by 1.2%
Lua et al.[71], 2019	Wood powder (WP) and polyurethane (PU).	Combined PU and WP for BPCM.	• The BPCM demonstrated exceptional thermal stability and phase change behavior throughout the solid-liquid phase change region. • BPCM has a peak solidification and melting latent heat of 132.4 J/g and 134.2 J/g, respectively, with 98.7% of the enthalpy efficiency.
Liang et al.[72], 2019	Polyethylene glycol (PEG) with wood flour (WF).	PEG and WF were used in the vacuum adsorption process.	• The quantity of PEG crystallization in the BPCM composite was decreased. • The melting temperature occurred had no relationship with the quantity of WF supplied or the length-to-diameter ratio.
Liu et al.[73], 2020	Polyethylene glycol (PEG) with Ca^{2+}-cross linked sodium alginate (SA)	PEG has been combined with Ca^{2+}-crosslinked SA.	• The PEG/SA composites (PSCs) had a 93% PEG loading level, and the phase change enthalpy could reach 156.8 J/g. • Good form stability and outstanding heat management properties.
Sheng et al.[74],2020	Pomelo peel foam (PPF), PEG, and MXene Nano-sheets.	PPF was incorporated into PEG and MXene nanosheets.	• The incorporation of MXene nanosheets into PPF improved the efficiency of light-to-heat conversion significantly. • The incorporation of PEG into form-stable composite PCMs (FCPCMs) rose from 86.9 wt% to 96.2 wt%, improving the thermal conductivity from 0.25 to 0.42 W/mK.
Hu et al.[75], 2021 .	Reduced graphene oxide (RGO) with spent coffee grounds (SCGs).	Produced BPCM with RGO and SCGs as a support structure.	• RGO-modified SCGs (SCGs@RGO) have a better 3-D porous structure than pure SCGs and can absorb 60.3 wt% polyethylene glycol. • Excellent leaking resistance and minor improvements in thermal conductivity. • SCGs@RGO has an extremely high ability of light-heat conversions, and retains solar heat in a short period of about 244 second of light
Sheikh et al.[76],2022	BPCM with copper foam matrix (CFM)	Incorporating BPCM composites into copper foam matrices with different pore densities and filling heights.	• BPCM/CFM with 95 PPI of pore density has the maximum cooling performance, with improvement ratios of 1.54 and 1.44 under 10 and 15 W of heat loads, respectively.
Suqing et al.[77],2022	Au-TiO_2 with PCM	Electrostatic adsorption and self-assembly are used to create microcapsules that combine PCM with photothermal catalysts (Au/TiO2).	• The average light-to-hydrogen efficiencies reached 11.4% and 5.0% for ATR@PCM and ATF@PCM, respectively, with an increase of 53.8% and 56.1% above their equivalent catalyst nanoparticle suspensions.
Xiao et al.[78], 2022	Loofah-based porous carbon (BPC) with Nano-Ag particles added and PEG.	PEG/BPC-Ag composite was produced by chemically reducing loofah-based porous carbon and adding Nano-Ag.	• The PEG/BPC-Ag BPCM photo-thermal conversion effectiveness was increased from 76.7% to 92.2% after the incorporation of Ag nanoparticles. • The BPCM's thermal conductivity which increased from 0.349 W/mK to 0.632 W/mK.PEG/BPC-Ag has thermal stability and reusability.
Du et al.[79], 2023	PEG and sandwich type composite foams (SCFs)	Using vacuum impregnation, PEG was embedded in sandwich-type composite foams consisting of melamine and bio-bacterial cellulose.	• Despite being exposed to 100 heat cycles, the composites retained their exceptional thermal stability.
Li et al.[80], 2023	Polyurethane (PU) and polylactic acid (PLA).	Polyurethane (PU) and polylactic acid (PLA) were combined to generate BPCM.	• The addition of PLA improves the leak-free performance and mechanical strength of the PLA/PU composite. • When the PLA component is 20% or 40% in the mixture of PLA/PU composites, the relative efficiency of enthalpy was 79.14% and 91.51% of the original
Alipour et al.[81], 2023	Decanoic acid (DA) and methyl palmitate (MP)	A BPCM was prepared using a eutectic combination of MP and DA.	• An eutectic mixture of 70% DA and 30% MP works best BPCM as a TES in building sector, and has 201.43 J/g and 202.3 J/g of latent heat of melting and freezing, and 20.19 °C and 15.08 °C of realistic melting and freezing temperatures.
Huang et al.[82], 2023	Biomass cellulose nanocrystals (CNCs), konjac glucomannan (KGM), MXene (a two-dimensional material), and $AgNO_3$.	CNCs, KGM, MXene, and AgNO3 were mixed together, then freeze-dried and annealed.	• PMCKA's features included high loading of 95.16%, high enthalpy of 231.38 J/g, exceptional conductivity of 147.5 S/m, with high stability cycle. • PMCKA has the ability to attain efficiencies for electro-thermal, and photo-thermal energy conversions of more than 98.9%, and 97.5%, respectively.
Masoud et al.[83], 2023	Oleic acid and Beeswax.	Beeswax and oleic acid were used with metal matrix sheets for cooling PV panels.	• Utilizing the BPCM decreases the temperatures of PV panels from 58.92 °C to 51.45 °C, however using MMS decreases PV temperatures compared to PV panels with PCM only, improving electrical efficiency.
Sheng et al.[84], 2023	PEG as BPCM and Wood flour (WF) and polylactic acid (PLA) as the matrix.	Impregnating PEG with WP and then combined with PLA.	• PEG was easily contained by WF owing to capillary forces. • The PEG/WF/PLA composite (WPC) retained their good latent heat of fusion 87.3 J/g when mixing by PLA. • WP improved PLA properties, such as mechanical strength, and processability at a wide range of temperatures.
McCord et al.[85], 2024	Palmitic acid (PA) and decanoic acid (DA).	Palmitic and decanoic acids were combined with sodium alginate and fiber flax, which were polypyrene coated.	• Polymerization was achieved uniformly using the PPy coating, giving a thermal conductivity of 0.453 W/mK. • BPCM made from the composite had a porous structure (porosity of 85%), allowing for good impregnation at 60% and 74% for DA and PA, respectively, hence energy storage and conversion capabilities. • Phase change enthalpy for BPCM with PA and DA was 100.98 J/g and 154.52 J/g, respectively.
Mert et al.[86],2024	Microporous polymers and oleic acid (OA).	OA was used as a matrix, together with microporous polymers and montmorillonite nanoclay.	• The composite BPCMs are suitable for cold thermal storage of energy uses such as building cooling, cold protection, and cold chain transportation due to their appropriate melting points of 7.08 °C and 7.40 °C, and moderate latent heat capacities.

4. Life cycle assessment of BPCMs

The sustainability indicators include biodegradability (biological degradation of substances) and energy efficiency (waste-free utilization of energy). Biomaterials for the production of BPCMs may be derived from natural sources, such as plant extracts, animal fats, or other biomass waste. This is more environmentally friendly than using PCMs from the fossil fuels such as petroleum [87]. To assess the total environmental impact of the BPCMs, a life cycle assessment needs to be carried out.

4.1. Raw material acquisition

The BPCM's life cycle begins with the extraction of raw materials (agricultural products, forest residues, or waste biomass). However, the usage of crops for food chain products could create doubts concerning land-use change and resource competition [88]. Some research shows that, in fact, agricultural residues or waste biomass (for example, rice husks, maize stalks, or algae) should be used because the problems of land uses conflicts are avoided in such cases [89]. Such an approach would help decrease the environmental impact. The energy consumed in processing raw materials plays an important role in the life cycle of BPCMs. In fact, biomass-based materials consume less energy compared to synthetic PCMs, particularly if the source material is waste biomass [88]. Also, using the renewable energy source during the processing phase decreases the carbon footprint of the product [44, 88].

4.2. Manufacturing of BPCM

The production process of BPCMs may include several stages, such as biomass extraction and pretreatment, phase-change material production, and other processes. The energy consumption of these operations may vary depending on the biomass area and the process used to produce PCMs. For instance, such mechanical operations, like transition from fatty acid to PCMs, should be carried out during chemical operations, which require considerable energy expenses, such as esterification [1]. Unlike regular PCMs, BPCMs have a smaller energy footprint because they can be produced from renewable resources via sustainable processes. Sustainable production of BPCMs is also practiced. Common practices include waste heat recovery and green chemistry techniques that eliminate the need for harmful solvents. Some other techniques that were developed recently and can be employed to reduce the impact of production of BPCMs on the environment include low-temperature processing and biocatalysis [90].

4.3. Uses of BPCM

One of the main advantages of BPCMs is their high capacity for heat storage and release compared with other PCMs, which may yield energy savings in building or TES applications. BPCMs gather heat during the day and give off heat at night; that is, they will be able to regulate temperature variation and reduce the energy consumption and greenhouse gas emissions due to reduced usage of active heating and cooling equipment [91]. Particularly in regions requiring extensive heating and cooling, it reduces energy consumption and greenhouse gas emissions. Up to 52.8% of electric energy use savings can be achieved from the LCA analysis of buildings fitted with BPCM [92], according to Mariela et al. The longevity, which retains phase change characteristics even under many temperature cycles, enhances the capacity of BPCMs to contribute to the thermal energy storage [44, 92].

4.4. Disposal stage of BPCM

In addition to the environmental benefits associated with the disposal of BPCMs compared with traditional PCMs, another benefit emerges. The negative environmental consequences related to buying these kinds of products become smaller due to the biodegradability of many of them [92]. BPCMs made of hybrid or artificial materials should be stored and reused to prevent depletion of environmental resources at the end of their life cycle. Researches are conducted in order to improve recycling procedures related to these kinds of materials, which will minimize the environmental impact of BPCMs as well [93]. One of the most discussed topics is related to the implementation of the circular economy concept based on the use of waste generated during the production of BPCMs in other energy forms or as biofuels and fertilizers [93]. Such innovations extend the useful life of materials and confer a more sustainable lifespan on BPCMs.

5. A critical analysis of the literature review

Based on the previously presented study, the utilization of various types of BPCMs, along with the improvements, barriers, and limitations affecting their applications in TES systems, can be analyzed as follows:

5.1. Advantages of employing BPCM vs petroleum PCMs in TES systems

PCMs produced from biological materials (BPCMs) have attracted widespread interest due to their ability to enhance energy efficiency and have a lower environmental impact than traditional PCMs derived from petroleum. The advantages and disadvantages of employing organic-based BPCMs and composite BPCMs in various TES systems, as well as their slight enhancements, will be identified in the subsequent critical analysis.

- BPCMs are made of sustainable materials, including agricultural residue and biological polymers. This supports environmentally friendly energy solutions while reducing dependence on petroleum-based sources. This is the major advantage of utilizing BPCMs.
- BPCMs have a lower carbon footprint than petroleum-based PCMs. They help prevent environmental degradation and the release of greenhouse gases.
- BPCMs are readily biodegradable and therefore remain environmentally friendly even after their useful life. However, some petroleum-based PCMs that may be difficult to remove.
- Finally, the toxic or hazardous elements that may be present in petroleum PCMs are typically absent from BPCMs, which facilitates compliance with requirements and improves workplace safety when BPCMs are used.

This analysis reviews the diverse applications of BPCMs across industries, including building heating and cooling, construction materials, refrigeration, textiles, waste heat recovery, and other industrial processes.

5.2. Barriers and limitations of employing BPCM in TES systems

Despite all of the advantages listed above, the comprehensive examination of the articles included in the current review demonstrates that BPCMs have intrinsic limitations, which can be summarized as follows:

- Due to limitations in phase-change temperature ranges, many BPCMs may be suitable only for a narrow range in TES applications.
- Organic BPCMs may have lower thermal conductivity. This caused lower heat absorption and release rates by limiting the PCM's heat-transfer capability compared with inorganic PCMs, which have better thermal conductivity. Furthermore, the addition of inorganic materials gives the potential to change this feature [94].
- BPCMs' long-term dependability in TES systems is influenced by their compatibility with storage systems, encapsulation materials, and heat transfer fluids. Adequate encapsulation is critical for BPCMs to maintain their effectiveness over time and to minimize leakage. It might be challenging to create stable, cost-effective encapsulation solutions that have no impact on the PCM's thermal properties. Poor compatibility with other materials may cause performance loss, leakage, or degradation.
- From an economic perspective, producing BPCMs, especially those manufactured from specialized feedstock can be more costly than producing conventional alternatives. Expansion may be challenging to accomplish with non-economic materials [95].
- Organic BPCMs, including saturated fatty acids synthesized from vegetable oil and animal fat, are selected TES due to their sustainability, biodegradability, and eco-friendliness. They have good melting and freezing ranges of temperature, enough latent heat of fusion, and lower changes in volume during the phase change; nonetheless, they may be crystallized with minimum supercooling [95].
- Studies have shown that the environmental and thermal advantages of BPCM are well known, but technical constraints on its practical application remain, especially regarding its stability over a few cycles of operation. As it was described in literature, some bio-based phase change materials, especially fatty acids, may suffer from a loss of thermal properties due to a large number of melting/freeze cycles, causing a drop in energy and phase transformation [30, 47]. This results from various degradation modes, including oxidation, partial evaporation, subcooling, and phase separation. Another challenge related to leakage is inadequate encapsulation, especially during repeated thermal stress on the material. To overcome these difficulties, the bio-based phase changing material is encapsulated in silica and graphene as nano-scale materials [59]. Furthermore, the introduction of thermally conductive nanomaterials, such as graphene [69] or copper oxide [70], could be applied to reduce the thermal stresses and increase the heat conductivity of the system, resulting in an increased thermal lifetime of the system. Moreover, using the combinations of different fatty acids, for example, lauric acid [30, 34], helps control the melting point and prevent the phase separation. Esterification of fatty acids enhances stability and makes them more resistant to oxidation [43]. Overall, it appears that overcoming the challenges associated with the application of the current BPCMs largely relies on chemical design and nanoengineering. This approach is promising, but further research is needed.

6. Conclusion

The fact that environmentally friendly materials can be degraded and reused is the fundamental advantage of employing these materials in sustainable applications. In contrast, this review focuses on the synthesis, composition, and utilization of bio-based phase change materials in thermal energy storage systems. The following conclusions were reached after studying 73 relevant research papers and analyzing the results:

- 1. Compared to the thermal characteristics of other biological materials, biocompatible bio-phase change materials offer several advantages, such as economic viability, lower environmental toxicity, and suitability for building applications.
- Composite bio-phase-change materials have significant benefits over conventional inorganic and organic phase-change materials in terms of their thermal conductivity. Undoubtedly, such combinations result in robust composites with high capacity for latent heat storage provided by the organic bio-phase-change material and improved thermal conductivity provided by the inorganic phase-change material. This, in turn, may reduce the volume variations in inorganic phase-change materials during phase change or material degradation.
- A variety of factors, particularly material composition and encapsulation techniques, can influence the reusability and thermal stability of bio-phase change materials, making them a viable alternative to petroleum-based phase change materials in many thermal applications.

- Applying bio phase-change materials to the interior of building envelopes decreased moisture inertia. However, the installation of bio-phase-change materials in the center and on the exterior side of envelopes substantially reduced energy consumption for cooling and heating. Additionally, by coupling the exterior gypsum board lining with a mat of bio-phase change materials, the duration of the wall's fire resistance increased.
- Combining bio-phase-change materials with renewable energy is an important future direction. The bio-phase-change materials could store excess energy produced during periods of maximum solar availability and use it during periods of minimal solar availability, thereby improving overall system performance. Combining bio-phase-change materials with microgrids and off-grid renewable energy systems offers significant potential in terms of energy balance and sustainability.

Author contributions statement

Conceptualization, Investigation, Writing- original draft, Abdulmunem R. Abdulmunem; Writing – review & editing, Habibah Ghazali; Formal analysis, Hasanain A. Al-Jaber; Validation, Data curation, Izhari Izmi Mazali; Project administration, Supervision, Pakharuddin Mohd Samin; Resources, Kamaruzzaman Sopian.

Data availability

The authors confirm that the data supporting the findings of this study are available within the article.

Declaration of interests

The authors declared that they have no competing financial or personal interests related to this work.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors declared that no generative AI or AI-assisted technologies were used in the writing process.

Nomenclatures

ALKs	Alkanes
APP	Ammonium polyphosphate
AWSC	Activated walnut-shell carbons
BC	Bacterial cellulose
BPC	Produce loofah-based porous carbon
BPCMs	Bio-based phase change materials
BS.HW	Lightened gypsum composite
BW	Beeswax
CA	Capric acid
CFM	Copper foam matrix
CNCs	Cellulose nanocrystals
CNT	Carbon nanotubes
COFA	Coconut oil fatty acids
CTW	Chemically treated wood
CuO	Copper oxide
DA	Decanoic acid
DSC	Differential scanning calorimetry
EP	Ethyl-palmitate
FA	Fly ash
FCPCM	Flexible composite PCM
FF	Flax fiber
FTIR	Fourier transforms infrared spectrophotometer
GW	Golden soy wax
HDPE	High-density polyethylene
HLC	Hemp lime concrete
KGM	Konjac glucomannan
LA	Lauric acid
LiA	Linoleic acid
LIB	Lithium-ion batteries
LOI	Limited oxygen index
LSF	Light gauge steel framed
MA	Myristic acid
MAGs	Monoacylglycerols
MF	Melamine foam
MMS	Metal matrix sheets
MP	Methyl palmitate
MPCM	Microencapsulated Phase change materials
MWPCM	Metallic wood-based Phase change materials
NW	Nature soy wax
OA	Oleic acid
O-Dt	Organic diatomite
PA	Palmitic acid
PCMs	Phase change materials
PEG	Propylene glycol
PFAD	Palm fatty acid distillate
PJ	Prosopis juliflora
PLA	Poly lactic acid
PO	Palm oil
PPF	Pomelo peel foam
PPy	Polypyrrole
PU	Polyurethane
PVC	Polyvinyl chloride
PW	Paraffin wax
RGO	Reduced graphene oxide
RWP	Recycled waste paper
SA	Sodium alginate
SC	Spent coffee
SCFs	Sandwich type composite foams
SCGs	Spent coffee grounds
TES	Thermal energy storage
TGA	Thermogravimetric analysis
WCF	Waste chicken feathers
WF	Wood fiber
WH	Wheat husk
WP	Wood powder
WS	Walnut shell
WSC	Walnut-shell carbons
xGnP	Exfoliated graphite nanoplatelets

References

[1] A. Sudeepthi, P. Arun, Exergetic performance evaluation of a phase change material integrated solar still. Journal of Thermal Engineering, 10(6)(2021),1423-1439. https://izlik.org/JA73SE62PB

[2] P. R. Gharde, S. N. Havaldar, Numerical investigation of an amalgamation of two phase change materials thermal energy storage system. Journal of Thermal Engineering, 10(2) (2021),263-272. https://doi.org/10.18186/thermal.1448527

[3] A. Kushwah, A. Kumar, M. K. Gaur, Techno-economic analysis of solar still with nano-phase change material and heating coil: A novel approach for sustainable development. Journal of Thermal Engineering, 11(2)(2021),476-492. https://doi.org/10.14744/thermal.0000928

[4] S. Aljabaır, I. Alesbe, S. H. Ibrahım, Review on latent thermal energy storage using phase change material. Journal of Thermal Engineering, 9(1) (2021), 247-256. https://doi.org/10.18186/thermal.1245298

[5] Abdulmunem, A.R., Mazali, I.I., Samin, P.M., Sopian, K. and Ghazali, H., 2026. Experimental assessment of sheep tail stearin as a sustainable phase change material in window-type solar air heater. Solar Energy, 310, p.114510. https://doi.org/10.1016/j.solener.2026.114510

[6] E. Gürsoy, Melting and energy storage performance enhancement of rectangular cavity with metal foam by nano-PCM and recessed/protruding dimpled fin wall. Journal of Energy Storage, 119(2025),116327. https://doi.org/10.1016/j.est.2025.116327

[7] E. Gürsoy, M. Gürdal, E. Gedik, Effect of Triangle Fin Inclination Angle and Aluminum Metal Foam on Melting Process in A Vertical Latent Heat Energy Storage System. Journal of Science, Technology and Engineering Research, 6(1) (2025), 11-30.

[8] A.M. Papadopoulos, State of the art in thermal insulation materials and aims for future developments, Energy and Buildings, 37(1)(2005),77-86. https://doi.org/10.1016/j.enbuild.2004.05.006

[9] Ye-chao Wan, Yan Chen, Zhi-xing Cui, Han Ding, Zhi Han, Jun-kai Gao, A promising form-stable phase change material prepared using cost effective pinecone biochar as the matrix of palmitic acid for thermal energy storage, Scientific Report 9 (2019), 11535. https://doi.org/10.1038/s41598-019-47877-z

[10] Murat Kenisarin, Khamid Mahkamov, Solar energy storage using phase change materials, Renewable and Sustainable Energy Reviews, 11 (9) (2007), 1913-1965. https://doi.org/10.1016/j.rser.2006.05.005

[11] Muhammad Faisal Junaid, Zia ur Rehman, Miroslav Čekon, Jakub Čurpek, Rashid Farooq, Hongzhi Cui, Imran Khan, Inorganic phase change materials in thermal energy storage: A review on perspectives and technological advances in building applications, Energy and Buildings, 252(2021),111443. https://doi.org/10.1016/j.enbuild.2021.111443

[12] Malik Muhammad Umair, Yuang Zhang, Kashif Iqbal, Shufen Zhang, Bingtao Tang, Novel strategies and supporting materials applied to shape-stabilize organic phase change materials for thermal energy storage–A review, Applied Energy, 235(2019),846-873. https://doi.org/10.1016/j.apenergy.2018.11.017

[13] Guruprasad Alva, Yaxue Lin, Guiyin Fang, An overview of thermal energy storage systems, Energy, 144(2018),341-378. https://doi.org/10.1016/j.energy.2017.12.037

[14] Belén Zalba, José M Marı n, Luisa F. Cabeza, Harald Mehling, Review on thermal energy storage with phase change: materials, heat transfer analysis and applications, Applied Thermal Engineering, 23(3)(2003),251-283. https://doi.org/10.1016/S1359-4311(02)00192-8

[15] R.K. Sharma, P. Ganesan, V.V. Tyagi, Long-term thermal and chemical reliability study of different organic phase change materials for thermal energy storage applications. J Therm Anal Calorim 124(2016),1357–1366. https://doi.org/10.1007/s10973-016-5281-5

[16] Caixing Chen, Hua Zhang, Xuenong Gao, Tao Xu, Yutang Fang, Zhengguo Zhang, Numerical and experimental investigation on latent thermal energy storage system with spiral coil tube and paraffin/expanded graphite composite PCM, Energy Conversion and Management, 126 (2016), 889-897. https://doi.org/10.1016/j.enconman.2016.08.068

[17] Jia-Nan Shi, Ming-Der Ger, Yih-Ming Liu, Yang-Cheng Fan, Niann-Tsyr Wen, Chaur-Kie Lin, Nen-Wen Pu, Improving the thermal conductivity and shape-stabilization of phase change materials using nanographite additives, Carbon, 51(2013),365-372. https://doi.org/10.1016/j.carbon.2012.08.068

[18] Zhu Jiang, Anabel Palacios, Boyang Zou, Yanqi Zhao, Weiyu Deng, Xiaosong Zhang, Yulong Ding, A review on the fabrication methods for structurally stabilised composite phase change materials and their impacts on the properties of materials, Renewable and Sustainable Energy Reviews, 159 (2022), 112134. https://doi.org/10.1016/j.carbon.2012.08.068

[19] Abdulmunem, A.R., Mazali, I.I., Samin, P.M. and Sopian, K., Beeswax as a sustainable thermal energy storage material: Experimental thermal assessment in solar air heater. Journal of Energy Storage, 103(2024),114398. https://doi.org/10.1016/j.est.2024.114398

[20] Abdulmunem, A.R., Mazali, I.I., Samin, P.M., Sopian, K. and Ghazali, H., Bio-phase change materials based on stearin of sheep tail-fats loaded with nanoparticles: Melting performance analysis in rectangular cavity as a sustainable building envelopes. Energy and Buildings, 336(2025),115612. https://doi.org/10.1016/j.enbuild.2025.115612

[21] Renquan Wu, Wei Gao, Yunhong Zhou, Zhuqi Wang, Qilang Lin, A novel three-dimensional network-based stearic acid/graphitized carbon foam composite as high-performance

shape-stabilized phase change material for thermal energy storage, Composites Part B: Engineering, 225 (2021), 109318. https://doi.org/10.1016/j.compositesb.2021.109318
[22] Lisa Boussaba, Amina Foufa, Said Makhlouf, Gilles Lefebvre, Laurent Royon, Elaboration and properties of a composite bio-based PCM for an application in building envelopes, Constr. Build. Mater. 185 (2018), 156–165. https://doi.org/10.1016/j.conbuildmat.2018.07.098
[23] Lisa Boussaba, Said Makhlouf, Amina Foufa, Gilles Lefebvre, Laurent Royon, Vegetable fat: a low-cost bio-based phase change material for thermal energy storage in buildings, J. Build. Eng. 21 (2019), 222–229. https://doi.org/10.1016/j.jobe.2018.10.022
[24] Gokhan Hekimoglu, Ahmet Sari, Turgay Kar, Sedat Keles, Kamil Kaygusuz, V. V. Tyagi, R.K. Sharma, Amir Al-Ahmed, Fahad A. Al-Sulaiman, Tawfik A. Saleh, Walnut shell derived bio-carbon/methyl palmitate as novel composite phase change material with enhanced thermal energy storage properties, J. Energy Storage 35(2021),102288. https://doi.org/10.1016/j.est.2021.102288
[25] Junqi Zhao, Yanchen Li, Xiaoyang Fang, Jingmeng Sun, Weiye Zhang, Beibei Wang, Xu Jianuo, Yi Liu, Hongwu Guo, High interface compatibility and phase change enthalpy of heat storage wood plastic composites as bio-based building materials for energy saving, J. Energy Storage 51 (2022), 104293. https://doi.org/10.1016/j.est.2022.104293
[26] Rachuri Naresh, Rajagopalan Parameshwaran, Vijayapuri Vinayaka Ram, Purgindla Venkata Srinivas, Study on thermal energy storage properties of bio- based n-dodecanoic acid/fly ash as a novel shape-stabilized phase change material, Case Stud. Therm. Eng. 30(2022),101707. https://doi.org/10.1016/j.csite.2021.101707
[27] R. Naresh, R. Parameshwaran, V. Vinayaka Ram, P.V. Srinivas, Bio-based hexadecanol impregnated fly-ash aggregate as novel shape stabilized phase change material for solar thermal energy storage, Mater. Today Proc. 56 (Part 3) (2022), 1317–1326. https://doi.org/10.1016/j.matpr.2021.11.320
[28] Ji Yong Choi, Beom Yeol Yun, Young Uk Kim, Yujin Kang, Sung Chan Lee, Sumin Kim, Evaluation of thermal/acoustic performance to confirm the possibility of coffee waste in building materials in using bio-based microencapsulated PCM, Environ. Pollut. 294 (2022), 118616. https://doi.org/10.1016/j.envpol.2021.118616
[29] Kaushik Biswas, Ramin Abhari, Low-cost phase change material as an energy storage medium in building envelopes: experimental and numerical analyses, Energy Convers. Manag. 88 (2014), 1020–1031. https://doi.org/10.1016/j.enconman.2014.09.003
[30] Kemal Cellat, Beyza Beyhan, Caner Güngor, Yeliz Konuklu, Okan Karahan, Cengiz Dündar, Halime Paksoy, Thermal enhancement of concrete by adding bio-based fatty acids as phase change materials, Energy Build. 106(2015),156–163. https://doi.org/10.1016/j.enbuild.2015.05.035
[31] Tor A. Vik, Habtamu B. Madessa, Petter Aslaksrud, Eirik Folkedal, Ottar S. Øvrevik, Thermal performance of an office cubicle integrated with a bio-based PCM: experimental analyses, Energy Procedia 111(2017),609–618. https://doi.org/10.1016/j.egypro.2017.03.223
[32] Yassine Kharbouch, Abdelaziz Mimet, Mohammed El Ganaoui, Thermal impact study of a bio-based wall coupled with an inner PCM layer, Energy Procedia 139(2017),10–15. https://doi.org/10.1016/j.egypro.2017.11.165
[33] Damien Mathis, Pierre Blanchet, Philippe Lagiere, Veronic Landry, Performance of wood-based panels integrated with a bio-based phase change material: a full-scale experiment in a cold climate with timber-frame huts, Energies 11 (11) (2018), 3093. https://doi.org/10.3390/en11113093
[34] Damien Mathis, Pierre Blanchet, Veronic Landry, Philippe Lagiere, Thermal characterization of bio-based phase changing materials in decorative wood-based panels for thermal energy storage, Green Energy Environ. 4 (1) (2019), 56–65. https://doi.org/10.1016/j.gee.2018.05.004
[35] Wu Dongxia, Mourad Rahim, Mohammed El Ganaoui, Rachid Bennacer, Rabah Djedjig, Bin Liu, Dynamic hygrothermal behavior and energy performance analysis of a novel multilayer building envelope based on PCM and hemp concrete, Constr. Build. Mater. 341(2022),127739. https://doi.org/10.1016/j.conbuildmat.2022.127739
[36] Roberto Bruno, Piero Bevilacqua, Bio-PCM to enhance dynamic thermal properties of dry-assembled wooden walls: experimental results, Build. Environ. 242(2023),110526. https://doi.org/10.1016/j.buildenv.2023.110526
[37] Z. Guermat, Y. Kabar, F. Kuznik, T.E. Boukelia, Numerical investigation of the integration of new bio-based PCM in building envelopes during the summer in Algerian cities, Journal of Energy Storage 79(2024),110111. https://doi.org/10.1016/j.est.2023.110111
[38] Hu Wen, Yu Xun, Thermal and mechanical properties of bio-based PCMs encapsulated with nanofibrous structure, Renew. Energy 62(2014),454–458. https://doi.org/10.1016/j.renene.2013.07.047
[39] Soroush Ebadi, SyedaHumaira Tasnim, Amir Abbas Aliabadi, Shohel Mahmud, Geometry and nanoparticle loading effects on the bio-based nano-PCM filled cylindrical thermal energy storage system, Appl. Therm. Eng. 141(2018),724–740. https://doi.org/10.1016/j.applthermaleng.2018.05.091
[40] Bence Németh, Ágnes S. Németh, Aurél Ujhidy, Judit Tóth, László Trif, János Gyenis, Tivadar Feczkó, Fully bio-originated latent heat storing calcium alginate microcapsules with high coconut oil loading, Sol. Energy 170(2018),314–322. https://doi.org/10.1016/j.solener.2018.05.066
[41] B.V. Rudra murthy, Veershetty Gumtapure, Thermal property study of fatty acid mixture as bio-phase change material for solar thermal energy storage usage in domestic hot water application, J. Energy Storage 25(2019),100870. https://doi.org/10.1016/j.est.2019.100870

[42] Lu Xiang, Jintao Huang, Benhao Kang, Teng Yuan, Qu Jin-ping, Bio-based poly(lactic acid)/high-density polyethylene blends as shape-stabilized phase change material for thermal energy storage applications, Sol. Energy Mater. Sol. Cells 192(2019),170–178. https://doi.org/10.1016/j.solmat.2018.12.036
[43] I.M. Rasta, I.N. Suamir, Study on thermal properties of bio-PCM candidates in comparison with propylene glycol and salt based PCM for sub-zero energy storage applications, IOP Conf. Ser. Mater. Sci. Eng. 494(2019),012024. https://doi.org/10.1088/1757-899X/494/1/012024
[44] Claudia Fabiani, Anna Laura Pisello, Marco Barbanera, Luisa F. Cabeza, Palm oil- based bio-PCM for energy efficient building applications: multipurpose thermal investigation and life cycle assessment, J. Energy Storage 28(2020),101129. https://doi.org/10.1016/j.est.2019.101129
[45] B.V. Rudra Murthy, Veershetty Gumtapure, Thermo-physical analysis of natural shellac wax as novel bio-phase change material for thermal energy storage applications, J. Energy Storage 29 (2020), 101390. https://doi.org/10.1016/j.est.2020.101390
[46] M. Nazari Sam, A. Caggiano, C. Mankel, E. Koenders, A comparative study on the thermal energy storage performance of bio-based and paraffin-based PCMs using DSC procedures, Materials 13 (2020), 1705. https://doi.org/10.3390/ma13071705
[47] Meysam Nazari, Mohamed Jebrane, Nasko Terziev, Multi-component bio-based fatty acids system as phase change material for low temperature energy storage, J. Energy Storage 39(2021),102645. https://doi.org/10.1016/j.est.2021.102645
[48] Shuang Liu, Wu Hao, Du Yu, Lu Xiang, Qu Jinping, Shape-stable composite phase change materials encapsulated by bio-based balsa wood for thermal energy storage, Sol. Energy Mater. Sol. Cells 230 (2021), 111187. https://doi.org/10.1016/j.solmat.2021.111187
[49] Ziyu Liu, Xingyue Zhu, Yazhou Tian, Kaiyun Zhou, Jue Cheng, Junying Zhang, Bio- based recyclable Form-Stable phase change material based on thermally reversible Diels–Alder reaction for sustainable thermal energy storage, Chem. Eng. J. 448 (2022), 137749. https://doi.org/10.1016/j.cej.2022.137749
[50] B.V. Rudra Murthy, Kumara Thanaiah, Veershetty Gumtapure, Experimental investigation of shellac wax as potential bio-phase change material for medium temperature solar thermal energy storage applications, Sol. Energy 231(2022),1002–1014. https://doi.org/10.1016/j.solener.2021.12.019
[51] Mohammad Hossein Jahangir, Mozhgan Ziyaei, Arash Kargarzadeh, Evaluation of thermal behavior and life cycle cost analysis of greenhouses with bio-phase change materials in multiple locations, J. Energy Storage 54(2022),105176. https://doi.org/10.1016/j.est.2022.105176
[52] Pin Jin Ong, Yihao Leow, Xiang Yun Debbie Soo, Ming Hui Chua, Xiping Ni, Ady Suwardi, Chee Kiang Ivan Tan, Rongyan Zheng, Fengxia Wei, Jianwei Xu, Xian Jun Loh, Dan Kai, Qiang Zhu, Valorization of spent coffee grounds: a sustainable resource for Bio-based phase change materials for thermal energy storage, Waste Manag. 157 (2023), 339–347. https://doi.org/10.1016/j.wasman.2022.12.039
[53] Abdulmalik Ismail, Jingyi Zhou, Anastasia Aday, Isabel Davidoff, Adewale Odukomaiya, Jialai Wang, Microencapsulation of bio-based phase change materials with silica coated inorganic shell for thermal energy storage, J. Build. Eng. 67(2023),105981. https://doi.org/10.1016/j.jobe.2023.105981
[54] Manisara Phiriyawirut, Nant Nammahachak, Pansanit Soongnok, Skan Thanunthaisong, Pongnatee Thanomkulbud, Pornkanok Chuenchitpisaikul, Surawut Chuangchote, Thanik Nithiphanthawong, Thana Sutthibutpong, Sutatch Ratanaphan, Elucidating the effects of emulsification on the thermal performances of palm oil-based phase change materials by molecular dynamics simulations, J. Energy Storage 64(2023),107071. https://doi.org/10.1016/j.est.2023.107071
[55] Abdulmunem R. Abdulmunem, Hussein M. Hamed, Pakharuddin Mohd Samin, Izhari Izmi Mazali, Kamaruzzaman Sopian, Thermal management of lithium-ion batteries using palm fatty acid distillate as a sustainable bio-phase change material, Journal of Energy Storage 73 (Part C) (2023), 109187. https://doi.org/10.1016/j.est.2023.109187
[56] Aman Yadav, M. Samykano, AK Pandey, Tareq Kareri, B. Kalidasan, Optimizing thermal properties and heat transfer in 3D biochar-embedded organic phase change materials for thermal energy storage, Materials Today Communications 38(2024),108114. https://doi.org/10.1016/j.mtcomm.2024.108114
[57] Aman Yadav, A.K. Pandey, M. Samykano, Tareq Kareri, V.V. Tyagi, Wheat husk derived microparticle infused organic phase change material for efficient heat transfer and sustainable thermal energy storage, Journal of Energy Storage 86 (PartA) (2024), 111204. https://doi.org/10.1016/j.est.2024.111204
[58] Su-Gwang Jeong, Jeong-Hun Lee, Jungki Seo, Sumin Kim, Thermal performance evaluation of bio-based shape stabilized PCM with boron nitride for energy saving, Int. J. Heat Mass Transf. 71(2014),245–250. https://doi.org/10.1016/j.ijheatmasstransfer.2013.12.017
[59] Yujin Kang, Su-Gwang Jeong, Seunghwan Wi, Sumin Kim, Energy efficient bio- based PCM with silica fume composites to apply in concrete for energy saving in buildings, Sol. Energy Mater. Sol. Cells 143(2015),430–434. https://doi.org/10.1016/j.solmat.2015.07.026
[60] Jiwon Yoo, SeongJin Chang, Seunghwan Wi, Sumin Kim, Spent coffee grounds as supporting materials to produce bio-composite PCM with natural waxes, Chemosphere 235(2019),626–635. https://doi.org/10.1016/j.chemosphere.2019.06.195
[61] Wu Dongxia, Mourad Rahim, Mohammed El Ganaoui, Rabah Djedjig, Rachid Bennacer, Bin Liu, Experimental investigation on the hygrothermal behavior of a new multilayer

building envelope integrating PCM with bio-based material, Build. Environ. 201(2021),107995. https://doi.org/10.1016/j.buildenv.2021.107995

[62] R. Parameshwaran, R. Naresh, V. Vinayaka Ram, P.V. Srinivas, Microencapsulated bio-based phase change material-micro concrete composite for thermal energy storage, J. Build. Eng. 39(2021),102247. https://doi.org/10.1016/j.jobe.2021.102247

[63] Xianxian Lin, Lu XinYu Chen, Danhong Hu Weng, Chendong Qiu, Pengwei Liu, Yi Zhang, Mizi Fan, Weisheng Sun, Xi Guo, In-situ copper ion reduction and micro encapsulation of wood-based composite PCM with effective anisotropic thermal conductivity and energy storage, Sol. Energy Mater. Sol. Cells 242(2022),111762. https://doi.org/10.1016/j.solmat.2022.111762

[64] Sudipta Halder, Jialai Wang, Yi Fang, Xin Qian, Muhammad Ali Imam, Cenosphere-based PCM microcapsules with bio-inspired coating for thermal energy storage in cementitious materials, Mater. Chem. Phys. 291(2022),126745. https://doi.org/10.1016/j.matchemphys.2022.126745

[65] Meysam Nazari, Mohamed Jebrane, Nasko Terziev, New hybrid bio-composite based on epoxidized linseed oil and wood particles hosting ethyl palmitate for energy storage in buildings, Energy 278(2023),127692. https://doi.org/10.1016/j.energy.2023.127692

[66] Khadidja Kehli, Belkacem Belhadj, Ahmida Ferhat, Development of a new lightweight gypsum composite: effect of mixed treatment of barley straws with hot water and bio-based phase change material on the thermo-mechanical properties, Constr. Build. Mater. 389(2023),131597. https://doi.org/10.1016/j.conbuildmat.2023.131597

[67] Yu Fan, Xiaomu Wang, Junying Zhang, Jue Cheng, Qingsong Lian, Relationship between cross-linking network structure and phase change performances toward multifunctional epoxy/bio-based wax form-stable phase change materials, Chem. Eng. J. 454(Part 2)(2023),140221. https://doi.org/10.1016/j.cej.2022.140221

[68] Yu Seulgi, Su-Gwang Jeong, Okyoung Chung, Sumin Kim, Bio-based PCM/carbon nanomaterials composites with enhanced thermal conductivity, Sol. Energy Mater. Sol. Cells 120 (Part B) (2014), 549–554. https://doi.org/10.1016/j.solmat.2013.09.037

[69] M. Al-Jethelah, S. Ebadi, K. Venkateshwar, S.H. Tasnim, S. Mahmud, A. Dutta, Charging nanoparticle enhanced bio-based PCM in open cell metallic foams: an experimental investigation, Appl. Therm. Eng. 148(2019),1029–1042. https://doi.org/10.1016/j.applthermaleng.2018.11.121

[70] Lu Xiang, Jintao Huang, Wai-Yeung Wong, Qu Jin-ping, A novel bio-based polyurethane/wood powder composite as shape-stable phase change material with high relative enthalpy efficiency for solar thermal energy storage, Sol. Energy Mater. Sol. Cells 200(2019),109987. https://doi.org/10.1016/j.solmat.2019.109987

[71] Bin Liang, Lu Xiang, Renpu Li, Weiping Tu, Zhuohong Yang, Teng Yuan, Solvent- free preparation of bio-based polyethylene glycol/wood flour composites as novel shape-stabilized phase change materials for solar thermal energy storage, Sol. Energy Mater. Sol. Cells 200(2019),110037. https://doi.org/10.1016/j.solmat.2019.110037

[72] Lu Liu, Xiaoqiao Fan, Yuang Zhang, Shufen Zhang, Wentao Wang, Xin Jin, Bingtao Tang, Novel bio-based phase change materials with high enthalpy for thermal energy storage, Appl. Energy 268(2020),114979. https://doi.org/10.1016/j.apenergy.2020.114979

[73] Xinxin Sheng, Dexuan Dong, Lu Xiang, Li Zhang, Ying Chen, MXene-wrapped bio- based pomelo peel foam/polyethylene glycol composite phase change material with enhanced light-to-thermal conversion efficiency, thermal energy storage capability and thermal conductivity, Compos. A: Appl. Sci. Manuf. 138(2020),106067. https://doi.org/10.1016/j.compositesa.2020.106067

[74] Hu Xinpeng, Haowei Huang, Hu Yubin, Lu Xiang, Yanlin Qin, Novel bio-based composite phase change materials with reduced graphene oxide-functionalized spent coffee grounds for efficient solar-to-thermal energy storage, Sol. Energy Mater. Sol. Cells 219(2021),110790. https://doi.org/10.1016/j.solmat.2020.110790

[75] Wu Dongxia, Mourad Rahim, Mohammed El Ganaoui, Rachid Bennacer, Bin Liu, Multilayer assembly of phase change material and bio-based concrete: a passive envelope to improve the energy and hygrothermal performance of buildings, Energy Convers. Manag. 257(2022),115454. https://doi.org/10.1016/j.enconman.2022.115454

[76] Yahya Sheikh, Mehmet Fatih Orhan, Mehmet Kanoglu, Heat transfer enhancement of a bio-based PCM/metal foam composite heat sink, Therm. Sci. Eng. Prog. 36(2022),101536. https://doi.org/10.1016/j.tsep.2022.101536

[77] Suqing Peng, Weilin Zhong, Hailun Zhao, Chao Wang, Zhipeng Tian, Riyang Shu, Ying Chen, Solar-driven multi-functional Au/TiO2@PCM towards bio-glycerol photothermal reforming hydrogen production and thermal storage, Int. J. Hydrog. Energy 47(98)(2022),41573–41586. https://doi.org/10.1016/j.ijhydene.2022.03.273

[78] Shikun Xiao, Hu Xiaowu, Lan Jiang, Yan Ma, Yinhui Che, Zu Shuai, Xiongxin Jiang, Nano-Ag modified bio-based loofah foam/polyethylene glycol composite phase change materials with higher photo-thermal conversion efficiency and thermal conductivity, J. Energy Storage 54(2022),105238. https://doi.org/10.1016/j.est.2022.105238

[79] Du Mingyue, Yao Chu, Mingyang Dong, Jin Zhang, Lingang Li, Yibing Cai, Bio- composite bacterial cellulose/melamine foam to prepare advanced phase change materials with sandwich structures for thermal storage and energy conversion, J. Energy Storage 66(2023),107381. https://doi.org/10.1016/j.est.2023.107381

[80] Zhuolin Li, Yu Zhigang Liu, Hao Wu Fang, Ran Niu, Wu Lida, Yi Li, Hu Miao Sui, Xiang Lu Wang, Qu Jinping, Bio-based polylactic acid/polyurethane blends with good recyclability and excellent shape stability for solar thermal energy storage, Sol. Energy Mater. Sol. Cells 258(2023),112406. https://doi.org/10.1016/j.solmat.2023.112406

[81] Anis Alipour, Fatemeh Eslami, Seyed Mojtaba Sadrameli, A novel bio-based phase change material of methyl palmitate and decanoic acid eutectic mixture: thermodynamic modeling and thermal performance, Chem. Thermodyn. Therm. Anal. 10(2023),100111. https://doi.org/10.1016/j.ctta.2023.100111

[82] Danyuan Huang, Zhibin Wang, Xinxin Sheng, Ying Chen, Bio-based MXene hybrid aerogel/paraffin composite phase change materials with superior photo and electrical responses toward solar thermal energy storage, Sol. Energy Mater. Sol. Cells 251(2023),112124. https://doi.org/10.1016/j.solmat.2022.112124

[83] Masoud Rahimi, Neda Azimi, Meriem Nouira, Amin Shahsavar, Experimental study on photovoltaic panels integrated with metal matrix sheets and bio-based phase change materials, Energy 262(Part A)(2023),125371. https://doi.org/10.1016/j.energy.2022.125371

[84] Mengjie Sheng, Yongji Sheng, Wu Hao, Zhigang Liu, Yi Li, Yang Xiao, Lu Xiang, Qu Jinping, Bio-based poly(lactic acid) shaped wood-plastic phase change composites for thermal energy storage featuring favorable reprocessability and mechanical properties, Sol. Energy Mater. Sol. Cells 252(2023),112186. https://doi.org/10.1016/j.solmat.2023.112186

[85] Maryam R. Yazdani McCord, Ari Kankkunen, Despoina Chatzikosmidou, Ari Seppälä, Jukka Seppälä, Hossein Baniasadi, Polypyrrole-modified flax fiber sponge impregnated with fatty acids as bio-based form-stable phase change materials for enhanced thermal energy storage and conversion, Journal of Energy Storage 81(2024),110363. https://doi.org/10.1016/j.est.2023.110363

[86] Mehmet Selçuk Mert, Emine Hilal Mert, Irena Pulko, Peter Krajnc, Hatice Hande Mert, Form-stable oleic acid based polyHIPE/nanoclay framework supported composite phase change materials for low-temperature latent heat storage, Thermal Science and Engineering Progress 50(2024),102569. https://doi.org/10.1016/j.tsep.2024.102569

[87] L. Ben-Alon, V. Loftness, K.A. Harries, E. Cochran Hameen, Life cycle assessment(LCA)of natural vs conventional building assemblies, Renewable and Sustainable Energy Reviews, 144(2021),110951. https://doi.org/10.1016/j.rser.2021.110951

[88] A. Kylili, PA. Fokaides, Life cycle assessment (LCA)of phase change materials (PCMs) for building applications: a review, Journal of building engineering 1 (6) (2016), 133-43. https://doi.org/10.1016/j.jobe.2016.02.008

[89] J.A. Noël, P.M. Allred, M.A. White, Life cycle assessment of two biologically produced phase change materials and their related products, Int J Life Cycle Assess 20(2015),367–376. https://doi.org/10.1007/s11367-014-0831-1

[90] P. Pawelzik, M. Carus, J. Hotchkiss, R. Narayan, S. Selke, M. Wellisch, M. Weiss, B. Wicke, M.K. Patel, Critical aspects in the life cycle assessment(LCA)of bio-based materials – Reviewing methodologies and deriving recommendations, Resources, Conservation and Recycling, 73(2013),211-228. https://doi.org/10.1016/j.resconrec.2013.02.006

[91] M.D. Heidari, D. Mathis, P. Blanchet, B. Amor, Streamlined Life Cycle Assessment of an Innovative Bio-Based Material in Construction: A Case Study of a Phase Change Material Panel. Forests. 10(2)(2019),160. https://doi.org/10.3390/f10020160

[92] Mariela Vega, Noelia Llantoy, Marta Chafer, Svetlana Ushak, Luisa F. Cabeza, Life cycle assessment of the inclusion of phase change materials in lightweight buildings, Journal of Energy Storage, 56(Part B) (2022), 105903, https://doi.org/10.1016/j.est.2022.105903

[93] M. Nazari, M. Jebrane, N. Terziev, Bio-Based Phase Change Materials Incorporated in Lignocellulose Matrix for Energy Storage in Buildings—A Review, Energies.; 13(12)(2020),3065. https://doi.org/10.3390/en13123065

[94] Ghani, Siti Amirah Abdul, Saidatul Shima Jamari, Sumaiya Zainal Abidin, Waste materials as the potential phase change material substitute in thermal energy storage system: a review, Chem. Eng. Commun. 208(5)(2021),687–707. https://doi.org/10.1080/00986445.2020.1715960

[95] John A. Noël, Laurent Kreplak, Nuwansiri Nirosh Getangama, John R. de Bruyn, Mary Anne White, Supercooling and nucleation of fatty acids: influence of thermal history on the behavior of the liquid phase, J. Phys. Chem. B 122 (51) (2018), 12386–12395. https://doi.org/10.1021/acs.jpcb.8b10568