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Review article

A comprehensive review of critical analysis of biodegradable waste PCM for thermal energy storage systems using machine learning and deep learning to predict dynamic behavior

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ABSTRACT

This article explores the use of phase change materials (PCMs) derived from waste, in energy storage systems. It emphasizes the potential of these PCMs in addressing concerns related to fossil fuel usage and environmental impact. This article also highlights the aspects of these PCMs including reduced reliance on renewable resources minimized greenhouse gas emissions and waste reduction. The study also discusses approaches such as integrating nanotechnology to enhance thermal conductivity and utilizing machine learning and deep learning techniques for predicting dynamic behavior. The article provides an overall view of research on biodegradable waste-based PCMs and how they can play a promising role in achieving energy-efficient and sustainable thermal storage systems. However, specific conclusions drawn from the presented results are not explicitly outlined, leaving room, for investigation and exploration in this evolving field. Artificial neural network (ANN) predictive models for thermal energy storage devices perform differently. With a 4% adjusted mean absolute error, the Gaussian radial basis function kernel Support Vector Regression (SVR) model captured heat-related charging and discharging issues. The ANN model predicted finned tube heat and heat flux better than the numerical model. SVM models outperformed ANN and ANFIS in some datasets. Material property predictions favored gradient boosting, but Linear Regression and SVR models performed better, emphasizing application- and dataset-specific model selection. These predictive models provide insights into the complex thermal performance of building structures, aiding in the design and operation of energy-efficient systems. Biodegradable waste-based PCMs' sustainability includes carbon footprint, waste reduction, biodegradability, and circular economy alignment. Nanotechnology, machine learning, and deep learning improve thermal conductivity and prediction. Circular economy principles include waste reduction and carbon footprint reduction. Specific results-based conclusions are not stated. Presenting a comprehensive overview of current research highlights biodegradable waste-based PCMs' potential for energy-efficient and sustainable thermal storage systems.

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1. Introduction

The excessive use of fossil fuels and reliance on non-renewable energy sources has been a growing concern in the development field since the last decade of the 20th century. This is a long-standing problem that has been difficult to address, due to a number of challenges, such as reducing usage, improving energy efficiency, and using sustainable resources. The construction industry is a major contributor to this problem, accounting for more than 33% of global energy consumption and 25% of global greenhouse gas emissions. Even though CO_2 emissions peaked in 2013 and then began to decline in 2016, emissions connected to buildings increased by 0.7% annually during the same time [1]. The European Union (EU) has acknowledged the significance of lowering greenhouse gas emissions and encouraging energy efficiency, especially in the building industry, as EU buildings consume a lot of energy and emit greenhouse gases. This is why the EU has taken steps to promote renewable energy and energy-efficient architecture [2,3]. Since thermal energy storage (TES) technology is in low demand, it is an effective strategy to promote sustainable energy techniques. TES enables the storage of thermal energy in specialized materials, which can subsequently be released as needed. The TES process utilizes both sensible and latent heat storage. These are the two primary ways that heat is stored. Latent heat storage requires the usage of certain materials that can change their phase at a given temperature to either absorb or release heat energy. Sensible heat storage refers to the process in which a material can absorb or release heat energy as a result of temperature changes [4,5]. The technology known as thermal energy storage (TES) includes two primary methods: systems that store sensible heat (SHTES) and systems that store latent heat (LHTES). SHTES structures often make use of low-cost materials like water, bricks, or rocks, which contribute to the technology's widespread adoption and long history of use. In contrast, low-temperature, high-energy-density storage (LHTES) systems make use of phase change materials (PCMs), which provide advantages such as increased energy density and a consistent working temperature. LHTES devices allow for a reduction in storage system size while maintaining efficiency because they can store 5–14 times more energy in the same volume as SHTES [6,7]. Transport and storage containers, clothes, pharmaceutical and food packaging, and electronics use Thermal Energy Storage (TES) using Phase Change Materials (PCMs). Fig. 1 (a and b) shows how PCMs' ability to absorb thermal energy and reduce heating and cooling is facilitated by their sensible and latent heat storage PCM's ability to absorb and release heat through multiple melting and freezing cycles.

The concept of PCM's capability of absorbing and releasing heat repeated melting and freezing cycles of Phase change materials (PCMs) is ideal for uses with a limited temperature range because they store a lot of heat during phase transformation shown in Fig. 1 [8]. These materials are used to cool electrical gadgets, recover waste heat, and build energy-efficient constructions. Numerical and experimental research on the usage of a carbon foam/PCM/nanocomposite material to manage energy consumption in electronic equipment and data centers [9,10]. Recently, these materials have been used in interior and water heating systems [11]. The transformation from solid to liquid and vice versa is one of the most common PCM conversions [12]. Their systems require careful encapsulation design because they are relatively non-hazardous in terms of toxicity and corrosiveness and experience only a modest density change during phase shifts. They are more expensive and have lower thermal conductivity [13,14]. PCMs have three subgroups: organic compounds, inorganic compounds, and combination compounds [15,16]. Solar concentrators use inorganic PCMs,

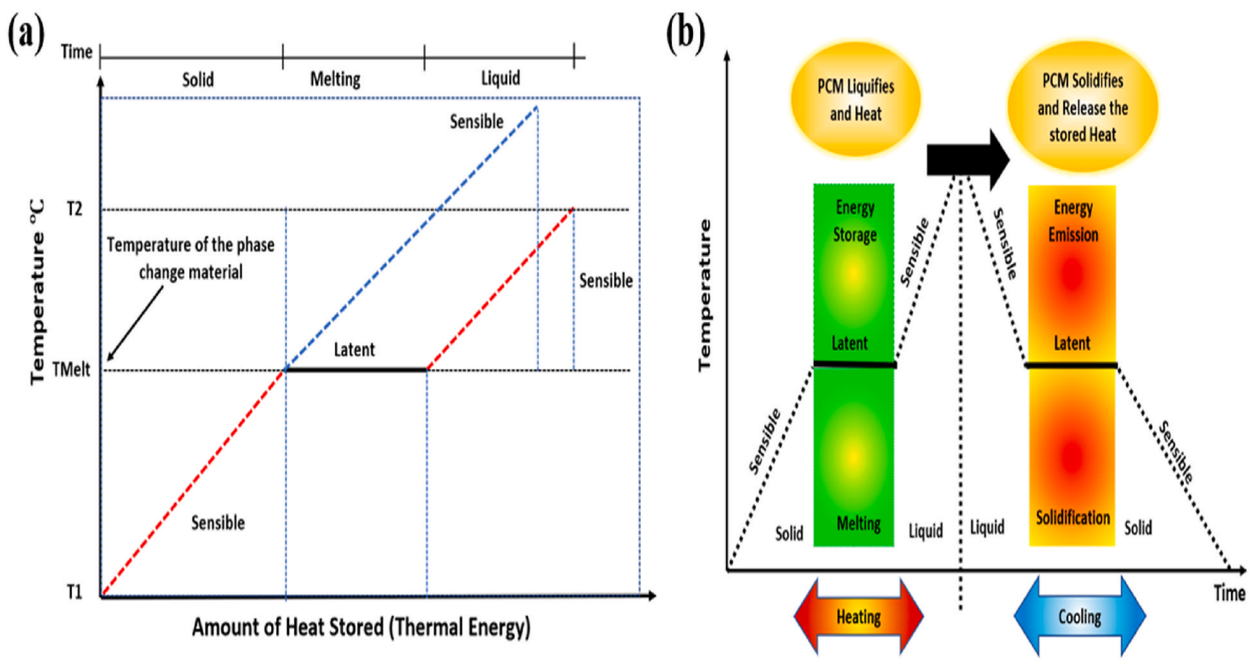

Fig. 1. (a) Sensible and latent heat phase change temperature profile (b) Heat-absorption and heat-release capabilities of PCM over repeated melting and freezing cycles.

specifically salts, for high-temperature operation. Organic PCMs have been used for decades in low-temperature solar thermal applications. Even after millions of charge and discharge cycles, fatty acids remain unaltered [17,18]. In comparison to water, organic and inorganic PCMs have similar thermal properties. The normal biological particulate carbon material has a density of 80% that of water, a specific heat capacity of half that of water, and an average latent heat of 150 MJ/m3. Artificial PCMs have a density sixty percent higher than water, yet their specific heat capacity is only fifty percent. However, inorganic PCMs have up to double the latent heat of fusion of biological ones [19] A drawback of this technique is that it takes a long time to recoup your initial investment. Repairing the PCM system without causing further damage is impossible, and the supercooling impact lowers the efficiency of the PCM material, leading to insufficient heat recovery. Scientists have tried enhancing PCMs by adding other chemicals, but this has backfired [20,21]. Adjustments prior to installation may be necessary since PCM materials have a very poor thermal conductivity, which limits heat transmission during the solid-liquid phase transition [22,23]. Phase segregation may occur in PCM with several components, reducing its long-term stability [24]. Organic PCMs can improve fire safety in building envelopes. Organic PCMs and fire retardants in building coverings can mitigate this [25,26]. Table 1 summarizes organic and inorganic PCM benefits and downsides [27]. Fig. 2 shows the Ideal characteristics of Bio-based PCM.

Renewable energies such as solar and wind are only available for a limited time, posing a challenge for their efficient utilization. Their supply is dependent on natural weather-related events, such as wind, rain, and sunlight, making it difficult to control. Efficient use of renewable energy can be achieved by storing it, thereby reducing reliance on fossil fuels, lowering system maintenance costs, and reducing energy wastage. Storing excess energy, whether short or long-term, is necessary for balancing energy production and consumption [28–30]. While electrical energy storage is expensive, thermal energy storage is cheaper. Thermal energy surplus reduces power grid peak demand but cannot be sold to the energy infrastructure. Battery and PCM energy storage devices. Users and researchers are investigating PCMs due to batteries' poor energy storage. Energy storage reduces energy use and expenses and offers a viable alternative energy supply, leading to major economic benefits [31–34].

Biodegradable waste as phase change material (PCM) in thermal energy storage systems is explored in this work. In this research, biodegradable waste, including agricultural produce and industrial trash, is harnessed to create a significant resource for energy efficiency. Machine learning and deep learning are used to forecast the dynamic behavior of PCM integrated building envelopes in this age of rapid technological improvement. These predictive models show complex building structure thermal performance, enabling more energy-efficient design and operation. NE-BB-PCM with homogeneous nano particles is also studied in this study. An examination into the two-stage synthesis of (NE-BB-PCM) opens new avenues for improving thermal conductivity and thermal energy storage system efficiency. This study evaluates bio-polymeric frameworks and biodegradable waste-based heat transfer fluids for PCM integration. These PCM innovation ideas are characterized and integrated in this research to improve energy storage system efficiency holistically. This pioneering work combines a biodegradable garbage, modern material science, and cutting-edge machine learning to promote sustainable thermal energy storage options. With a synergistic approach and interdisciplinary collaboration, this research creates a paradigm for using waste materials and predictive innovations to convert energy-efficient architectural systems and ecological preservation.

1.1. Understanding the different types of phase-Changing materials

Phase-change PCMs store and release thermal energy. The heat turns solids into liquids and back. Due to this phase change, PCMs can control TES apparatus temperature. PCMs must maintain temperature during phase transition. Temperature-controlled

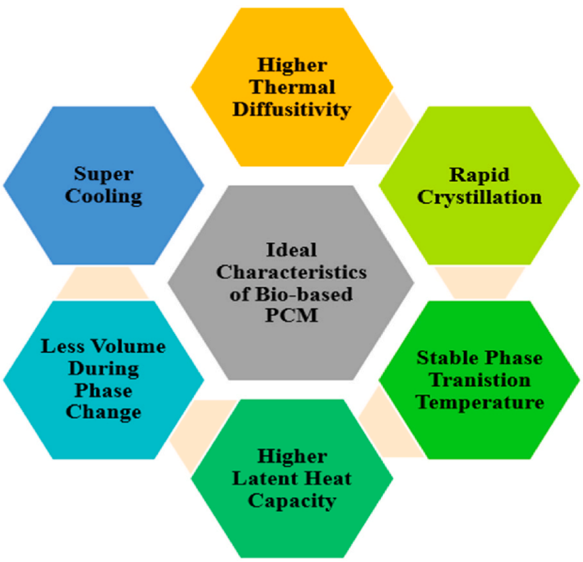

Fig. 2. Ideal characteristics of bio-based PCM

applications benefit from their high heat of fusion and phase shift heat absorption/release. Because PCMs retain their chemical and physical properties despite heating and cooling, they are reliable [35]. Materials phase-change from −5 °C to 190 °C. Its adaptability makes PCMs useful in cold chain logistics, building insulation, and solar energy storage. Organic, inorganic, and eutectic are the three types of PCMs. PCM includes paraffins, glycols, polyols, fatty acids, and esters! PCMs include copper, salt, and molten hydrates. Organic and inorganic materials make eutectic PCMs with specific phase variations. Specific applications demand PCM characteristics. Features allow phase transition and high melting point [36]. Heat transport and phase transition heat fusion are needed for energy storage and release. Phase change, low supercooling, and thermal stability persist. Popular PCMs must be profitable. Also desirable are segregation-free self-nucleating PCMs. PCM component phase transition isolation may reduce performance. PCMs must adjust for heat regulation and energy storage. They are a feasible alternative for many sectors since they store and release thermal energy at exact temperatures and maintain quality through several cycles [37,38]. Phase transition materials are classified in Fig. 3 and listed in Table 1 as Metallics, Non-Paraffin Organics, Hydrates Salts, and Paraffin Wax. Non-paraffin organics and liquid-to-gas PCMs are examples. Instead of paraffin wax PCMs, we use metallic PCMs at high temperatures.

1.2. Thermal energy storage incorporating with bio-based phase change material

Organic fatty acid ester compounds known as bio-based PCMs are produced from sustainable feedstocks such underutilized animal and vegetable fats. These innovative PCMs made of organic materials are less flammable than paraffins. Bio-based PCMs may be mass-produced and are less expensive than paraffins. They work well when used in construction materials for thermal energy storage. PCMs that are frequently researched and sold are non-renewable, such as salt hydrates and paraffin. The extraction process involves using mirabilite as the solvent for obtaining sodium sulphate decahydrate [40]. Considering the increasing significance of TES in the context of the energy transition and the quantities of energy storage materials that will be required in the future, it is evident that the development of PCMs non-depletable resources will be essential for ensuring a sustainable energy future. Future waste management and recycling systems are a significant aspect of sustainability. An increase in the use of biodegradable and compostable PCMs could be a step towards more sustainable TES [41]. Bio-based raw materials have been explored for decades in other fields like plastic manufacture, but PCMs from they are novel. Bio-based polymers are not biodegradable or compostable, like fossil-based plastics, but they are similar in manufacture and end-life sustainability. Bio-based PCMs contain biomass, vegetable, tropical, or animal/fish fats. Biodegradability must be researched for each type of bio-based PCM, even though it is generally assumed. Generally benign, biobased PCMs can be employed in low to high temperatures (−80 to 275 °C) [42].

1.3. Various bio-based phase change materials and their types

The term "bio-based PCMs" refers to a class of organic fatty acid ester materials or compounds produced from renewable and ineffective feedstocks like vegetable and animal fats. They represent a relatively novel class of organic-based PCMs and are discovered to be much less flammable than paraffin. As a result, the economics of bio-based PCMs are more favorable than those of paraffin and they can be produced on a wide scale [43].. Because of this, it is thought to be effective to apply them to building fabrics in order to get good thermal energy-storage capabilities. Three main biodegradable waste sources for bio-based phase change materials (BB-PCMs)

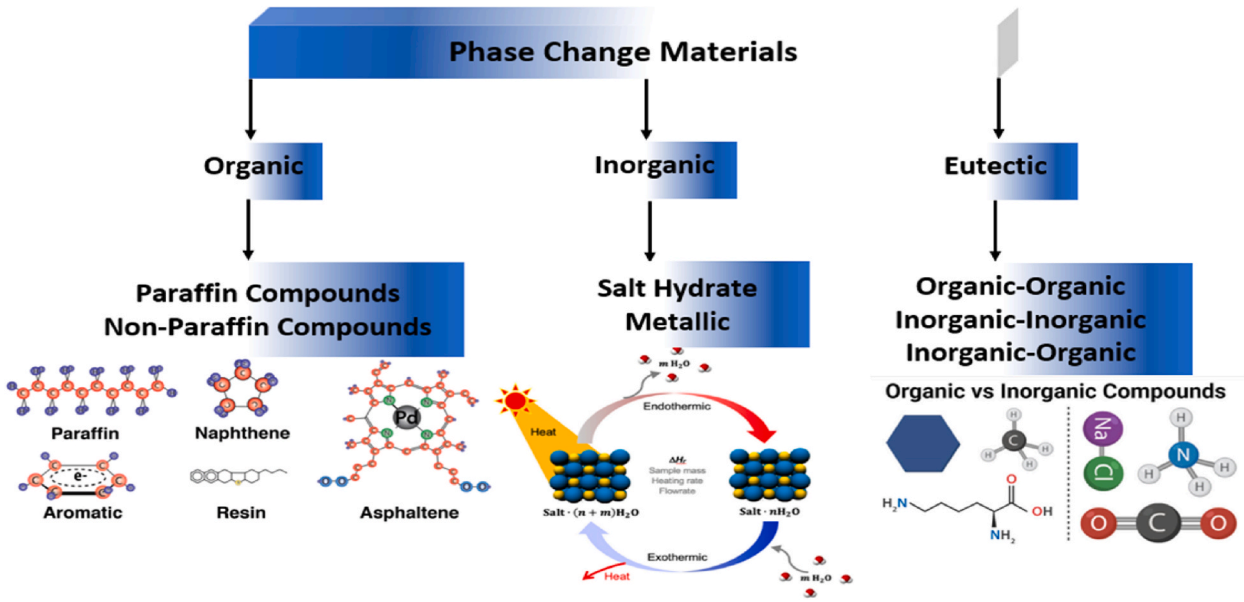

Fig. 3. Shows the classification of phase change materials [39].

are agricultural, food, and industrial. These categories have chemical compositions and properties appropriate for PCM production. Agricultural waste's high cellulose and lignin concentration makes it a prospective PCM source. Acid hydrolysis, pyrolysis, and carbonization can convert it. Rice straw, corn stalks and sugarcane bagasse are PCM-potential agricultural waste. Due to its high lipid content, food waste can be converted into PCM through transesterification, acid-catalyzed esterification, and enzymatic esterification. Waste cooking oil, pig fat, and fish oil are PCM prospects. Due to its high organic content, industrial waste is a rich PCM resource. Chemical modification, encapsulation, and impregnation can convert industrial waste into PCM. Industrial waste polystyrene, polyethylene, and paraffin can be PCM sources shown in Fig. 4. Biodegradable garbage from various sources can be used to store thermal energy. Agricultural waste, food waste, and industrial waste are potential sources of PCM that have been investigated in the literature. Rice straws, corn stalks, and sugarcane bagasse are examples of agricultural waste that have been used to synthesize PCM through acid hydrolysis, pyrolysis, and carbonization [44]. Waste cooking oil, waste animal fat, and waste fish oil are examples of food waste that have been used to synthesize PCM through transesterification, acid-catalyzed esterification, and enzymatic esterification [45]. Waste polystyrene, waste polyethylene, and waste paraffin are examples of industrial waste that have been used to synthesize PCM through chemical modification, encapsulation, and impregnation [46].

In -Corporation Techniques of Bio-Based Phase Change Materials. BPCMs fabrication methods are divided into two types (a) direct incorporation method and (b) indirect incorporation method, as shown in Fig. 5. The direct incorporation methods are immersion, absorption, recyclable trash, and economic framework. Use waste cooking oils, fatty acids, and bee wax to make a biodegradable composite at low cost is the easiest option. The indirect approaches are micro-, macro-, shape-, and form-stable. Micro- and macro-encapsulation is used to prevent leakage from BPCM due to its flexibility, high surface area, thermal stability, and corrosion resistance. The most studied and likely used BPCMs for TES applications with low carbon release [47,48]. BPCMs possess a renewable, less explosive, and eco-friendly, low vapor pressure, a chemically stable inflammable, on-explosive, broad range of melting temperatures, high density, and recyclable nature, which allows them for several applications [49,50]. Moreover, the excess availability at a low cost of BPCMs makes them favored choices somewhat over conventional PCMs [51]. BPCMs are preferred over the other PCMs due to their significant properties, as shown in Fig. 4.

2. Incorporation Technologies of bio based PCM

Traditional BPCM, such as vegetable oil, animal fat, and fatty acids, exhibit respectable TES characteristics. Most are currently biodegradable and utilized as biodegradable PCMs in a variety of applications. Tri-esters (sometimes referred to as triglycerides), which are three long-chain fatty acids, are combined to create an animal fat and vegetable oils. Fig. 5(a) utilizes glycol and fatty acids to create the tryster, while alcohol groups are utilized as nucleophiles. The agricultural and food industries produce non-conventional BBPCMs that are not standardized, including animal fat waste, non-edible oils like chicken feather, lard, and tallow [52]. TES uses animal fat waste and non-edible oils because they contain fatty acids and have good thermal properties. There is some preliminary study in this area. BB-PCM is made utilizing non-edible animal fat and a biocatalytic reaction, as shown in Fig. 5(b). Waste edible oils from dyeing, fuel, and bio-based plasticizers [53], bio-lubricants, bio-origin solvents for pollutants [54], 2nd generation biofuel/gas

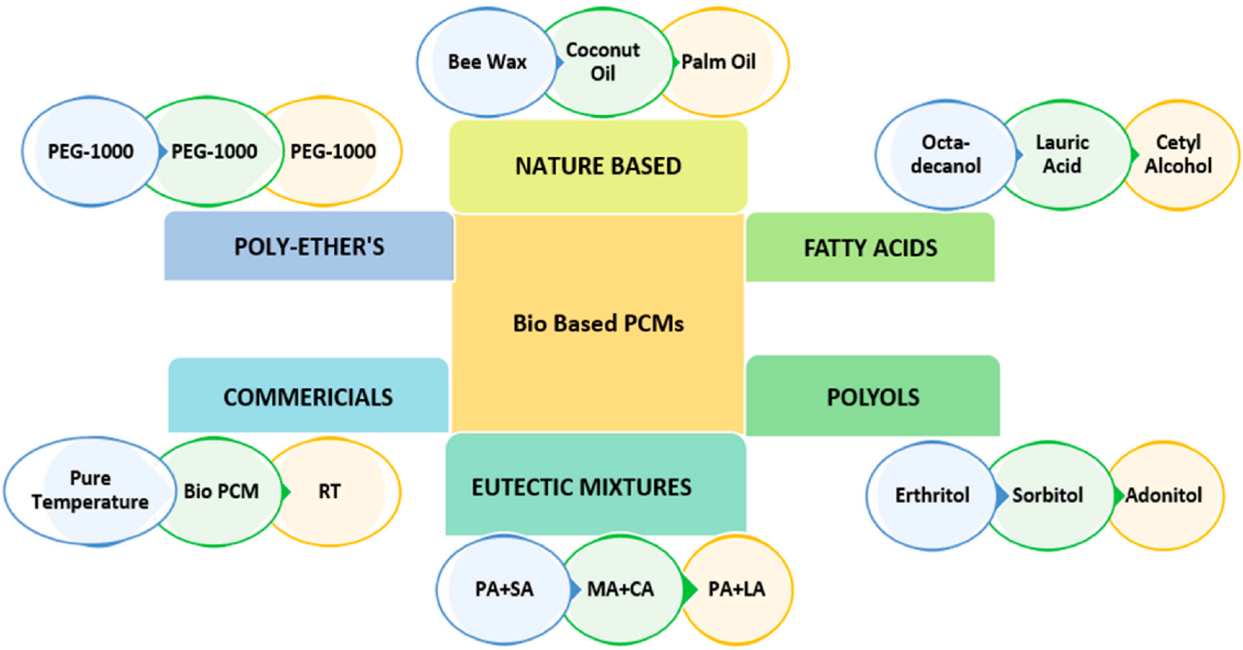

Fig. 4. classification of bio-based phase change materials.

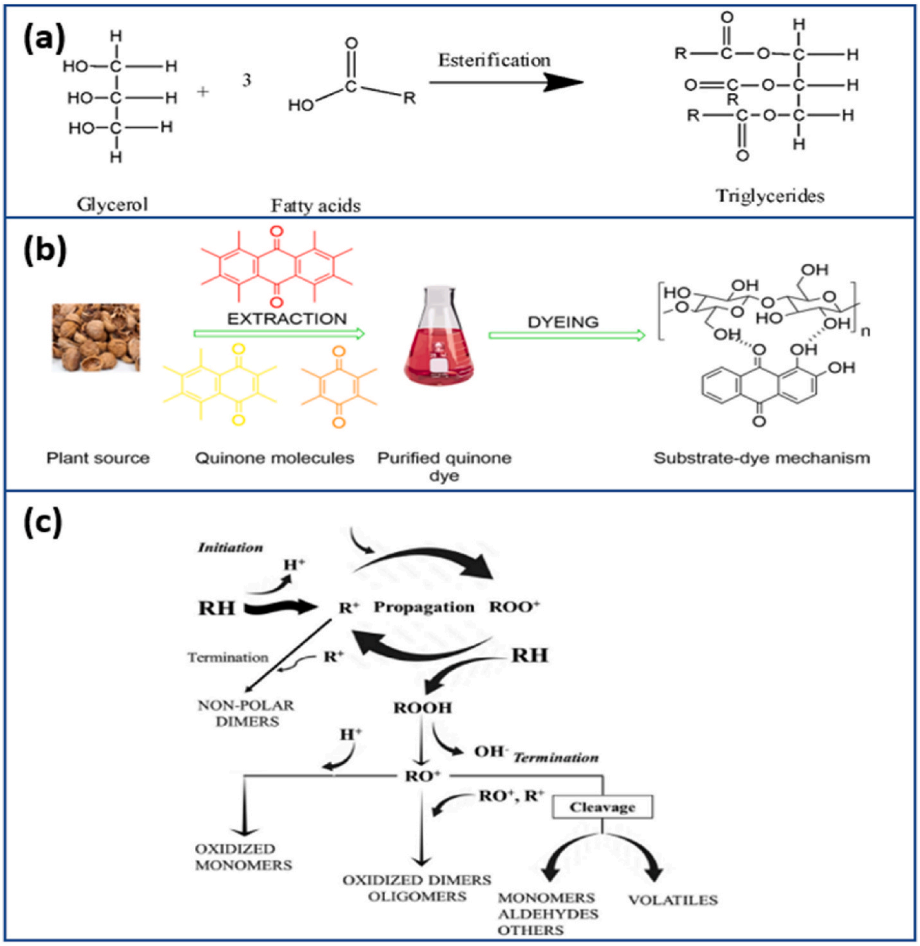

Fig. 5. (a) Assembly of tri -esters, (b) Fabrication of BPCM from non-conventional materials Plant Source using the biocatalytic reaction, and (c) Assemblies of WEOs with fatty acids [56,57].

polyamide for and asphalt binder additive are used for rejuvenating aged-bitumen [55] In TES applications, BPCMs showed notable properties. WEO assemblies with fatty acid bonding angles are shown in Fig. 5 (c). Direct integration, indirect incorporation, recycled waste, immersion, assimilation, macro-, micro-, physical-, and form stability. Physical mixing, nanoparticle surface modification, and encapsulation minimize BPCM matrix degradation. Ultrasonication, direct immersion, vacuum impregnation, macro/-microencapsulation, and direct impregnation are further ways are shown in Fig. 6. Microencapsulation was a common method used for BBPCMs. We need to find the best BPCM encasing materials because they raise production costs.

3. Selection criteria for bio-based phase change material (BB-PCM)

Several selection considerations must be considered before PCMs may be used for passive cooling in the building envelope and reduce cooling system energy demands and indoor temperature changes. The PCM's freezing point should be between 10 and 30 °C to physically maintain a comfortable indoor temperature. The average day and evening temperatures and other climatic parameters at the place of work should be considered when choosing this temperature [58,59]. As a consequence of the increased energy absorption and emission capabilities of the PCM, the building envelope can be made thinner and lighter. The Cp (specific heat capacity) also needs to be high [60]. There can be no thermodynamics without efficient heat transmission. Instantaneous temperature reactions occur when the thermal conductivity is strong. When considering a PCM, thermodynamic qualities are the most critical to consider, although chemical properties such as chemical stability, minimal volume expansion, and low or no super-cooling during freezing are also crucial [61–63]. Fig. 7 presents the selection criteria determined by the PCM's properties.

Additives and surfactants are tested to increase phase transition materials' cooling and chemical stability. An electric heating source is cooled by surfactant-induced Pure Temp phase transition material and graphene nanoplatelets [64]. Thermal energy capacity, phase change enthalpy, reference temperature duration, and conductivity assess cooling. BPCM integration technology and significant publications. Energy-efficient and warm. Problem fixed with PCMs. Energy-storage PCMs excel at matching supply and demand. PCM-infused sensible water tanks could boost hybrid latent heat storage energy density and at 15% PCM, water storage tanks

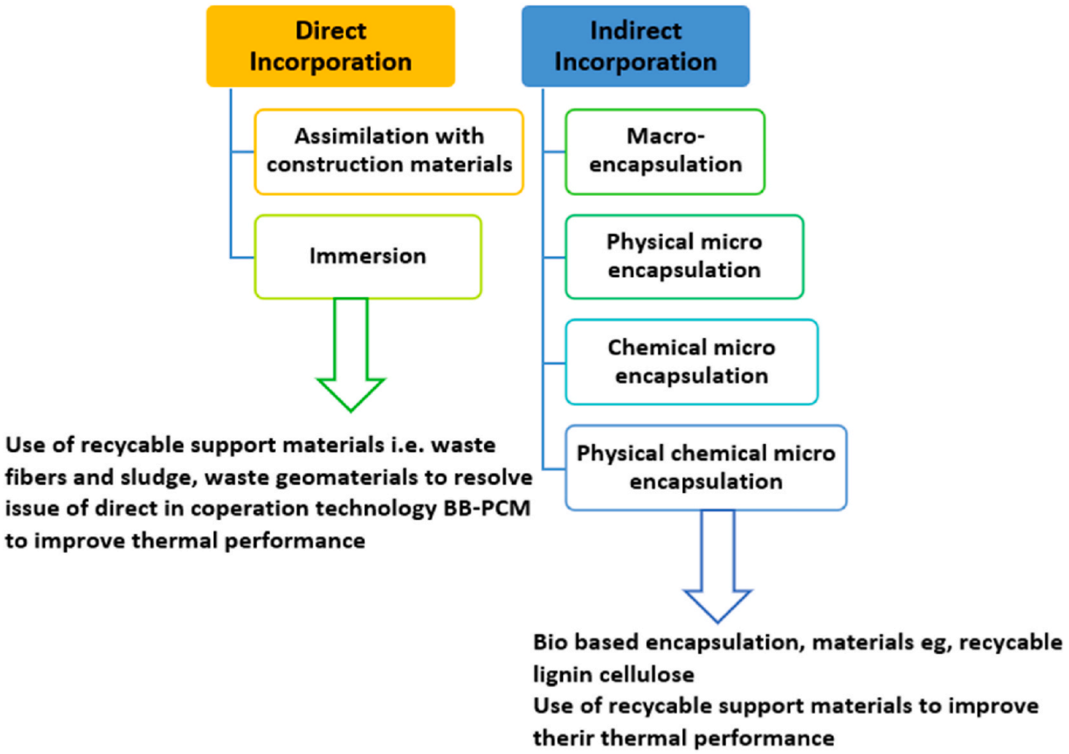

Fig. 6. Incorporation technologies of BB- PCM [57].

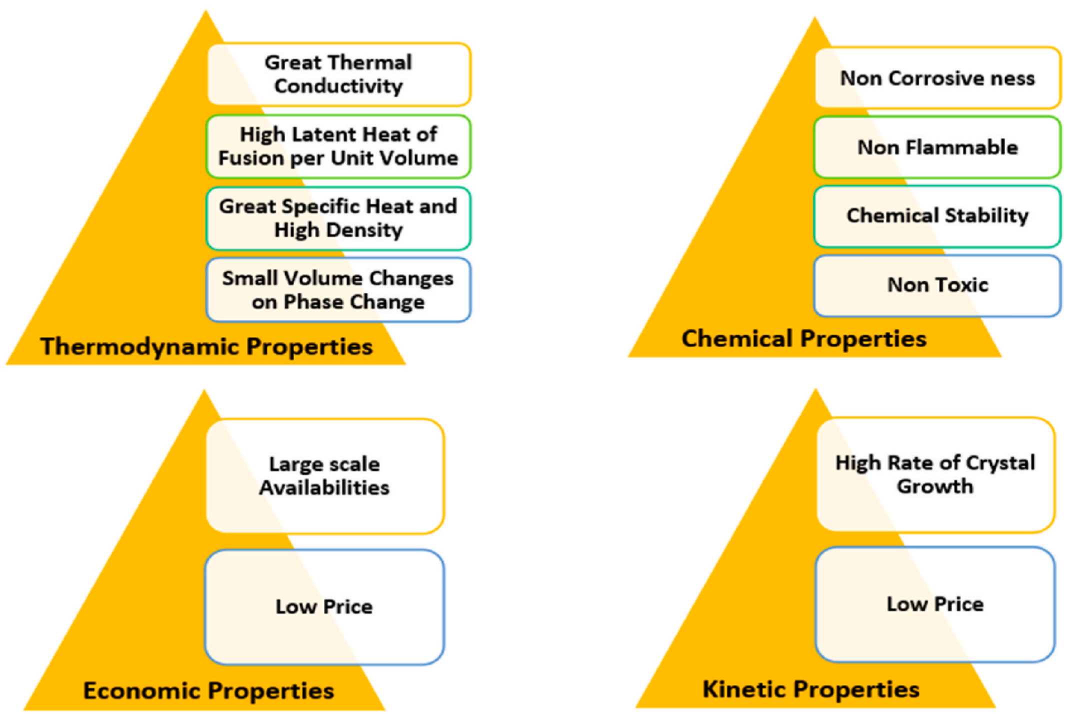

Fig. 7. Selection criteria based on PCM characteristics.

retained 70% more heat. Active and passive PCM research reduces building cooling and heating expenses. The literature suggests BB-PCMs save 44.16 percent on building energy. BB-PCMs alter TRC thermal and mechanical performance, claims this study. Thermal and mechanical tests were performed on the new BB-PCMs -TRC model. The BB-PCMs -TRC saves 37% more energy and 4° lowers peak temperatures. Eco-friendly constructions improve thermal mass with wood-based polymer composites (BPCMs). Phase transition, bio-based matrices, and mixes are issues [65–69]. Bio-based energy management materials can be made using renewable and sustainable BPCMs and wood-based matrices. PCM and passive natural ventilation were used to calculate cooling energy savings in a moderate-climate workplace. 8%–15% cooling energy reductions were reported. PCM efficiency rose 8% with natural ventilation. Between the years 2016 and 2022, research was conducted on a variety of PCMs for potential usage in construction-related applications [70–74]. Table 4 shows the results of research done on several important PCMs during this period. Between the years 2019 and 2022, the primary experimental research on passive application of thermal energy storage and the experimental research on passive applications has been done on PCM-integrated building components is carried out in Tables 2 and 3.

4. Thermophysical characteristics of bio based PCM derived from biodegradable waste

The literature has examined the thermal characteristics of PCM made from biodegradable waste. It has been discovered that the source of the waste and the synthesis technique affect the specific heat capacity and latent heat of fusion of PCM made from biodegradable waste. The thermal conductivity of PCM from biodegradable waste is generally lower than that of conventional PCMs, which may limit their use in certain applications [86–88].

4.1. Thermal energy storage system

Technology for thermal energy storage (TES) allows for the storage and later release of energy during periods of low energy consumption. Energy load shifting (TES) is seen as one of the most potential technologies for lowering peak demand during peak usage times (Off-peak hours). There are three possible types of heat storage in TES systems Fig. 8. Displays a variety of techniques for the storage of thermal energy.

4.2. Thermal conductivity

A material's thermal conductivity is its capacity to conduct heat. The material is better for storing heat if it conducts it quickly. Due to their poor thermal conductivity however, PCMs have been fortified with high-conductivity nanoparticles. The development of nanotechnology has made it possible to manufacture tiny particles. Metals, metal oxides, CNTs (multi-walled and single-walled carbon nanotubes), graphene, graphite etc. are just some examples of the nanoparticles that are utilized regularly. Fig. 4. Displays the numerous factors influencing the NEPCM's thermal conductivity. Most research focuses on the enhancement of thermal conductivity in base phase transition materials through the incorporation of nanoparticles. A noteworthy exception is the work of Colla et al. [90], who demonstrated an 8% reduction in heat conductivity upon the addition of alumina nanoparticles to paraffin. However, the authors did not provide a clear explanation for this observation. The integration of nano-enhanced phase transition materials is expected to decrease heating, melting, and solidification durations due to heightened thermal conductivity. Notably, thermal conductivity exceeding 100% was measured. Graphene nanoplatelets were introduced into phase change materials based on Lauric acid, carbon, and magnesium chloride hexahydrate [91,92]. Elevating nanoparticle concentration within phase change materials augments heat conductivity. Nevertheless, a challenge arises from the propensity of high nanomaterial concentrations to induce nanostructure aggregation within the underlying phase change material. This aggregation exhibited a dual effect on thermal conductivity – enhancing it in certain scenarios while diminishing it in others. This intricate interplay could potentially yield misleading outcomes concerning the thermal conductivity of nano-enhanced phase transition materials. The unpredictability of nanoparticle agglomeration stems from factors such as nanoparticle morphology, concentration, the type of base phase change material, phase duration, and temperature [93].

4.3. Factors Affecting Thermal Conductivity

Early studies on nano fluid heat conduction show enhancement of up to 40% in TC with a nanoparticle concentration of less than 5%. Different mechanisms also have been proposed for this anomalous enhancement which include static mechanisms—nano layering,

Table 1
PCM types include Paraffin Wax, Non- Paraffin Organics, Hydrates Salts and Metallics.

Property or characteristic	Hydrated salts	Metallics	Paraffin wax	Non paraffin wax
Thermal conductivity	High	Very high	Very low	Low
Heat of fusion	High	Medium	High	High
Corrosive	Corrosive	Varies	Non-corrosive	Mildly Corrosive
Melt Temperature (°C)	60 to 300	25 to 100	200 to 280	90 to 250
Latent heat (KJ/kg)	60 to 300	25 to 100	200 to 280	90 to 250
Weight	Light	Heavy	Medium	Medium
Thermal cycling	Unstable over repeated cycles	Stable	Stable	Elevated temperature can cause decomposition

Table 2
PCMs that were investigated for use in thermal energy storage applications between the years 2016 and 2022.

PCM Type	Shell material	Category of PCM	Melting Point (°C)	Latent Heat of Solidification	Thermal Conductivity (W/m·K)	Ref.
RT 18	Steel	Organic	18	220	0.21	[64,75]
Lauric Acid & Capric Acid	Stainless Steel	Fatty Acids	20	190	0.18	[76]
RT 21	Furnace Dust	Paraffin	21	210	0.17	[76]
Hexadecane	Copper	Paraffin	22	200	0.16	[75]
Intertek	Polymer	Organic	23–27	180	0.15	[77]
PEG 600	PVC	Polymer	21–25	160	0.14	[75,76]
1-Dodecanol & Capric Acid	Aluminum	Fatty Acid & Alcohol	26	150	0.13	[75,78]
SP 25	Aluminum	Salt Hydrate	26	140	0.12	[75,76]
CaCl2	PVC	Salt Hydrate	25–27	130	0.11	[75,79]
RT 27	Aluminum	Organic	28	120	0.10	[75,76]
RT 28	/	Organic	28	110	0.09	[78]
RT 28HC	Aluminum	Organic	27–29	100	0.08	[75,76,78]
MG29	Glass	Paraffin	27–29	90	0.07	[78]
Capric Acid	Aluminum	Fatty Acid	30	80	0.06	[75,78]
Salt Hydrate	Polymer	Salt Hydrate	31	70	0.05	[80]
RT 35	Aluminum	Organic	28–35	60	0.04	[75,78]
Capric Acid & Palmitic Acid	Gypsum Wallboard	Fatty Acids	26	50	0.03	[75,78]
Capric Acid & Myristic Acid	Polystyrene	Fatty Acids	26	40	0.02	[76]
Tetradecanoyl & Myristic Acid	PE-RT	Fatty Alcohol & Fatty Acid	29–32	30	0.01	[75]

Table 3
Between 2019 and 2022, the primary experimental studies on passive applications were carried out on building components incorporating PCMs.

PCM	Material	PCM form	T_{melt} (°C)	Test Scale	Result and remark	Ref.
RT28HC	Aluminum panel	macro	28	Field test	The radiative panel and PCM led to a 0.8 °C reduction in cooling load, peak temperature, and average temperature.	[79]
PX 35	Aluminum panel	Micro	35	Field test	To prevent summer warmth in double skin facades, the PCM blind stabilized air temperature between the glass layers.	[78]
Paraffin	Concrete panel	SSPCM (paraffin + graphite	25.5	Field test	PCM roofs reduced indoor air temperature 7%–15%. High-reflectivity roofs lowered the roof surface temperature by 2.2 °C and internal air temperature by 8.5%–17.0%.	[77]
Paraffin	Polyurethane membrane	SSPCM	25, 31 and 44	Lab test	PCMs cooled materials and indoors. Dark membranes work better at 31–45 °C phase shift temperatures than cool roof materials (25–35 °C).	[80]
Paraffin	Wood fiber-polymer Composite	Nano	27.4	Lab and Field test	40 wt% PCM reduced wood fibre composite tensile and bending strength by 58% and 68%, respectively. Overheating (temperatures above 23 _C) is 50% reduced by PCM and natural night airflow.	[81]
Coconut oil	Pouches	Marco	22.6	Field test	South-facing PCM walls and windows reduced interior temperatures by 7.2 _C. Wall-only PCM drops 5.2 _C.	[82]
N-octadecane	Plaster wallboard	Nano	22.3	Field test	Summer night-time ventilation is necessary since the PCM (30 wt%) stabilized the interior temperature.	[83]
RT28	TES from different places in the window	Macro	27.8	Field test	The PCM improved window heat balance by 10% in winter but overheated in summer.	[84]
N-octadecane (RT26)	Embedded copper or PVC tubes in insulated panels	Macro	32.2	Field test	Compared to a normal insulation panel, the PCM (12–15%) reduced wall peak heat flow by 12%–33%. Copper encapsulated better than PVC.	[85]

aggregation and percolation, interface thermal resistance, fractal geometry, and dynamic mechanisms, Brownian motion, the ballistic nature of nanoparticles, and nanoscale convection shown in Fig. 9 [94].

4.3.1. Brownian motion of the nanoparticles

In nanofluids, nanoparticles move in three ways. Force, temperature differential, and concentration gradient cause Brownian, thermophoretic, and osmophoretic motions. Brownian motion—the random motion of nanoparticles in the base fluid due to continual bombardment of particles and base fluid molecules—linked the abnormal improvement in nanofluid TC [95]. A high nanoparticle volume-to-area ratio enhances thermal transmission during Brownian motion due to particle-particle interaction. Another is particle-fluid interaction-induced micro-convection heat transfer. Brownian motion has a greater impact on the thermal conductivity

Table 4
A comparison table of PCM materials' thermal conductivities, production processes, and synthesis/characterization methods.

Ref.	PCM Material	Synthesis Technique	Characterization Technique	Manufacturing Method	Thermal Conductivity
[133]	Paraffin wax	Emulsion polymerization	DSC, TGA, XRD, SEM	Casting, compression molding, extrusion	0.2–0.4 W/mK (solid), 0.12–0.19 W/mK (liquid)
[134]	Fatty acids	Chemical reaction with alcohol	DSC, TGA, XRD, FTIR	Casting Compression Molding	0.2–0.3 W/mK (solid), 0.14–0.19 W/mK (liquid)
[30]	Salt Hydrates	Dissolution And Recrystallization	DSC, TGA, XRD, FTIR	Mixing, Encapsulation	0.2–1.5 W/mK (solid), 0.5–3 W/mK (liquid)
[135]	Eutectic Mixtures	Mixing Of Two Or More Materials	DSC, TGA, XRD, SEM	Casting, Compression Molding	0.2–0.4 W/mK (solid), 0.15–0.25 W/mK (liquid)
[136]	Graphene-Based phase change Material	Chemical Vapor Deposition Exfoliation, Reduction	Raman Spectroscopy, SEM, TEM	Mixing, Coating	2000–5000 W/Mk
[137]	Glauber's Salt	Crystallization From Aqueous Solution	DSC, TGA, TRD, FTIR	Encapsulation, Impregnation	1.6–2.6 W/mK (solid), 2.2–2.8 W/mK (liquid)
[138]	Bio-Based Materials	Extraction From Natural Sources	DSC, TGA, XRD, SEM	Compression Molding, Solvent Casting	0.1–0.6 W/mK (solid), 0.1–0.3 W/mK (liquid)
[139]	Metal-Organic	Coordination Self Assembly	DSC, TGA, XRD,	In Situ Growth Deposition	0.2–2.5 W/Mk
[140]	Carbon Based phase change materials	Carbonization Of Natural Precursors	Raman spectroscopy, SEM	Mixing Coating	10–1000 W/mK
[141]	Phase Change Emulsions	Emulsion Polymerization, Solvent Evaporation	DSC, TGA, XRD, FTIR	Emulsion Blending, Spray Drying	0.2–2.5 W/mK

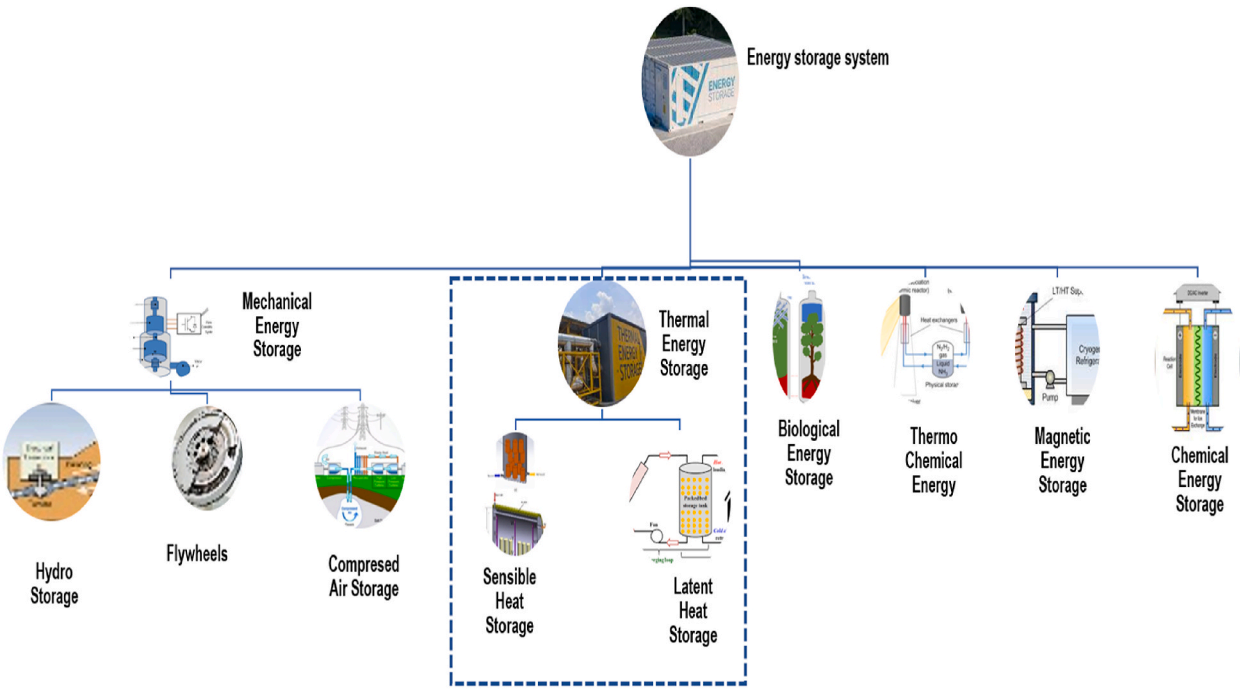

Fig. 8. Different thermal energy storage systems [89].

of nanofluids than thermal and osmotic motion [96,97].

4.3.2. Nanolayer effect

The particle-fluid force generates the ordered solid-fluid interface called the nanolayer. According to reports, nanolayer TC is higher than bulk base fluid and lower than nanoparticle TC [97]. TC enhancement of nanofluids is caused by the nanolayer's thickness increasing the concentration of nanoparticles in the base fluid, acting as a thermal bridge [95]. A particle-fluid interaction creates "Kapitza resistance" that hinders heat transport and lowers system TC. Nanolayer thickness is a nano meter, yet nanoparticles' high specific surface area makes the nanolayer effect crucial for heat transfer across the particle-fluid interface [96].

4.3.3. Nanoparticle clustering

A nanoparticle constituent of nanofluid clusters as collision distance decreases due to the weak force of attraction (van der Waals)

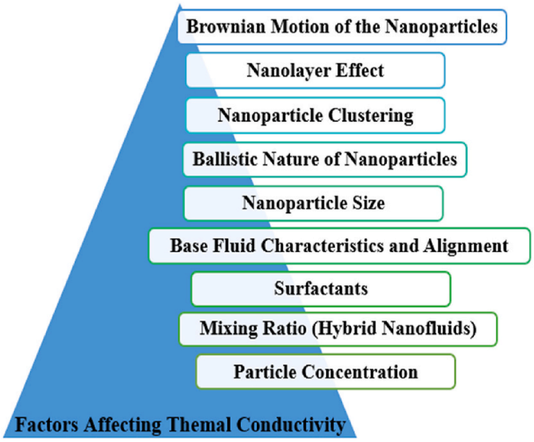

Fig. 9. Factors affecting thermal conductivity.

[97]. High nanoparticle concentration promoted clustering. Nanofluid TC is improved by nanoparticle clustering [98]. Localized rich-particle portion development lowers heat transfers thermal resistance compared to less-particle section. Settlement of heavier aggregates reduces TC by creating bigger particle-free areas. The cluster of nanoparticles in the nanofluid transfers heat faster than the less-particle region [95].

4.3.4. *Ballistic nature of nanoparticles*

Heat is carried in solids and micro scales when photons are dispersed randomly. Vibrating solid atoms can result in the transfer of heat. Hot locations with high phonon densities transmit heat via phonon diffusion due to temperature gradients. Since nanoparticles are smaller than phonon heat transmission techniques, their ballistic behavior is simple. Reducing nanoparticle size in a nanofluid increases ballistic phonon transmission [99–101].

4.3.5. *Nanoparticle size*

Particle size makes classification and identification distinctive due to crucial properties. Nanoparticle size affects nanofluid formulation nomenclature and thermal and convective properties. Nanoparticle sizes affect nanofluid thermal conductivity and stability. Changes in nanoparticle size cause changes in nanofluid thermal conductivity. Since nanoparticle size is reduced, nanofluid enhancement is linked to nanolayer thickness, clustering, surface area, convection, and Brownian motion [98,102].

4.3.6. *Base fluid characteristics and alignment*

Nanofluid composition and application require base fluid polarity, viscosity, and hydrogen bonding. Choosing, experimental, and nanofluid applications require knowledge of these two basic materials and their properties. Nanoparticles with varied chemical and physical characteristics are hard to suspend in base fluids. Thermal conductivity is highly affected by base fluid molecule and suspended nanoparticle thermal interfacial resistance. Base fluids with high polarization spread metal oxide nanoparticles. Base fluids EG and EG-W were tested on 4 vol% Sic nanofluids with varied nano-sizes [103–105].

4.3.7. *Surfactants*

Surfactants in nanofluid formulations stabilize them and prevent segregation and settlement. Nanofluid stability affects Thermal conductivity. Nanofluid thermal conductivity increases at low surfactant concentration and decreases at high concentration. Surfactant (SDBS) weight fraction, stability, and pH affect 0.05 wt% TC [103].

4.3.8. *Mixing ratio (hybrid nanofluids)*

Variations in mixing ratio (20:80–80:20) and temperature (30–80 °C) improved the thermal conductivity of 1 vol% TiO_2–SiO_2/water–EG (60:40) nanofluid by 16% (peak) at 80 °C. Using a 40:60 (MgO–ZnO) mixing ratio at 50 °C increased the thermal conductivity of 0.1 vol% MgO–ZnO/DIW nanofluids by 15–22% [106,107].

4.3.9. *Particle concentration*

Nanofluid is made by suspending nanoparticles in a base fluid. Nanoparticle concentration increases directly with nanoparticle suspension in the base fluid. Nanoparticles should increase the thermal conductivity of the nanofluid due to Brown motion and other factors. Classical studies evaluated TC for mono-particle and hybrid nanofluids at room temperature, but later work assessed it at different temperatures [108,109].

5. Sustainability aspects of bio-based phase change materials (BPCMS), sustainability of BBPCM considering various aspects

Bio-based phase change materials (BPCMs) provide many environmental benefits. These elements come from biomass, vegetable oils, and animal fats. They lessen dependence on scarce fossil fuels and contribute to a sustainable resource base. Compared to fossil fuel-based PCMs, BPCMs have a lower carbon impact. This is noteworthy. These commodities reduce greenhouse gas emissions, which helps combat climate change and align with global carbon reduction efforts [110]. BPCM waste is reduced by using animal fat and non-edible oils. Trash rerouting and landfill/incinerator reduction improve trash management. Degradability is crucial because bio-based goods decay naturally without harming the environment. Circular economy concepts include using waste materials to make BPCM to extend their useable life, improve resource efficiency, reduce virgin resource exploitation, and reduce waste. Local sourcing is beneficial for bio-based products [111]. Increase local economies, reduce transportation-related carbon emissions, and strengthen supply linkages. The natural BPCM production uses less energy than non-renewable extraction and processing. As opposed to non-renewable extraction and processing. Efficiency conserves energy and makes the industry more sustainable. BPCMs use non-edible oils and agricultural waste to help farmers generate income and be environmentally friendly. Effective land management, less agricultural waste, and environmental stewardship can result [112].

Renewable resources, decreased carbon footprint, waste reduction, biodegradability, circular economy alignment, energy efficiency, local sourcing, agricultural benefits, biocompatibility, and participation in research and innovation make bio-based phase change materials sustainable. Sustainability requires careful consideration of many factors and a life cycle review, like any material. Construction PCMs must be successful, cost-effective, repay, eco-friendly, and socially responsible. Fig. 6 presents the PCM and building investigation conceptual framework for long-term viability. This section only discusses PCM performance, pricing, and their impact on the current situation. The next parts examine PCM manufacturing's social pressures and lifecycle research. Examined data from numerous research scenarios and applications to assess building PCMs' environmental impact depicts in Fig. 10. Because there is limited evidence in the literature, life cycle assessment (LCA) calculations will be done to examine the environmental impact next.

6. Synthesis techniques of PCM

PCM synthesis from organic waste has been studied in several ways. Chemical modification converts biodegradable waste into PCM through esterification, transesterification, and hydrogenation. Biodegradable garbage is encapsulated in polymers, silica, or metal shells. Impregnating silica gel or activated carbon with biodegradable waste. A NEPCM is a liquid-solid combination with uniformly dispersed nanoparticles that do not agglomerate or alter chemically [113]. One- and two-stage NEPCM synthesis are used. NPs are synthesized and disseminated in the starting PCM in one step. The nanoparticles are dispersed into the base PCM in the second phase. The two-stage procedure was used in most investigations. The two-step NEPCM synthesis uses vacuum impregnation, mixing, ultrasonication, fundamental mixing, autoclave, absorption, one-pot, and facial solution blending. Blending and ultrasonication are popular in science. Particles with high thermal conductivity can be mixed with PCMs two ways [114]. PCMs that don't accomplish anything can be absorbed into the supporting substance's pores. Composites having 3D structures or two-dimensional structural additions reduce phonon dispersion and increase NEPCM thermal conductivity. A modest amount of high-thermal-conductivity material can boost PCM's thermal conductivity. In the 1-dimensional or 0-dimensional framework, the PCM enables heat conduction. It increases heat conductivity by prolonging phonon mean free routes [104]. Purified PCM must be odor- and contamination-free before creating NEPCM. Purified PCM was degaussed in a vacuum furnace above its melting point, cooked in a drying oven and vacuum-dried [115, 116]. NPs were heated to remove moisture Mixing and ultrasonicating the nanoparticle PCM slurry involves melting pure PCM, adding NPs, surfactants (if synthesizing NEPCM), and melting while Mixing takes 1–3 h [117–119]. NP agglomeration can be reduced by ultrasonicating the NEPCM mixture, but it depends on the time and frequency of the ultrasonication. Higher frequencies impair NP

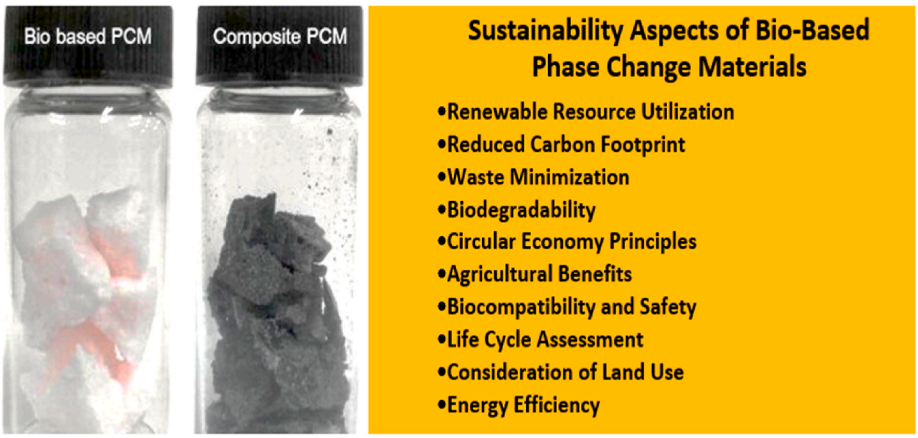

Fig. 10. Sustainability of PCM in buildings: A conceptual framework for research.

stability and enhance sedimentation. Ultrasonic heat can impair NP morphology found to be 32–50 kHz [120,121]. Table 4 shows the comparison of PCM materials' thermal conductivities, production processes, and synthesis/characterization methods shown in Fig. 15 and Table 5 shows review on the characterization of Nano-enhanced Bio Base PCM Thermophysical Properties.

6.1. Manufacturing a bio-based phase-change material with nanomaterials

Bio-enhanced phase change materials can be made in several ways. In situ, interface, suspension, emulsion, and sol-gel encapsulation are the most frequent approaches. The procedure depends on the PCM and product qualities. A monomer is polymerized in situ with a PCM. The PCM is protected from deterioration and leakage by the polymer shell. Polymerizing two monomers at the PCM-liquid interface is interfacial polymeric. A thin polymer layer encases the PCM. A PCM is suspended in a liquid monomer and polymerized in suspension polymerization. The polymer is a PCM matrix. Cross-linking the gel creates a solid matrix that encases the PCM. Selection of materials and procedures is crucial for bio-enhanced PCM preparation. The polymer matrix should have good mechanical properties and be able to withstand thermal cycling of the PCM, the encapsulation process should be efficient and produce a high yield of microcapsules, and the microcapsules should be uniformly sized and shaped. Traditional petroleum-based PCMs may be less environmentally friendly than bio-enhanced ones. Biodegradable and renewable, they can be made. Developing and improving bio-enhanced PCMs for thermal energy storage, heat transfer, and medication administration is ongoing. Manufacturing Bio-based PCM with Enhanced Nanoparticles The low heat conductivity of PCM prevents its widespread application. To improve performance, add greater conductivity elements to the PCM's dispersion. Increased PCM nanoparticle dispersion improves heat transmission and conductivity, according to studies. Adding nanoparticles to PCM is called nanoparticle-enhanced PCM. Fig. 11 a and b shows (a) simultaneous creation and dispersion of nano enhanced bio based PCM, (b) Methods for Preparation Bio Enhanced Phase Change Materials. BBPCM was traditionally created in one or two steps. Creation and dissemination of nanoparticles occur simultaneously in a single phase. NEBBPCM is usually made via heat evaporation.

The two-step process is the recommended approach for NEBBPCM preparation. Nanoparticles, nanofibers, and nanotubes are created through chemical or physical processes in the first step of the two-step approach. Next, high-shear mixing and homogenizing are used to combine the liquid PCM and nanoparticles. It's cheaper and easier to make a lot of nanoparticles using this method [122]. The vast majority of scientists have used the two-step strategy to design effective NEBBPCM.

Table 5
A review table on the characterization of Nano-enhanced Bio Base PCM Thermophysical Properties.

Ref.	NEPCM Material	Technique/Instrument Used	Working Principle	Thermophysical properties
[142]	RT 23	Differential Scanning Calorimetry (DSC)	Measurement of Heat Flow	Melting and solidification temperatures, enthalpy of melting and solidification, and thermal conductivity were measured.
[143]	RT158	Transient Hot Wire Technique	Measurement of Thermal Conductivity	An enhancement in thermal conductivity was observed with the addition of graphene oxide to the RT58 NEPCM
[144]	Lauric Acid	Hot Disk Transient Plan Source (TPS)	Measurement of Thermal Conductivity	It was found that as the temperature of the NEPCM rose, so did its thermal conductivity.
[145]	Paraffin Wax	Differential Scanning Calorimetry (DSC)	Measurement of Heat Flow	Increasing the cooling rate was discovered to increase the NEPCM's thermal hysteresis.
[146]	Erythritol	Laser Flash Technique	Measurement of Thermal Diffusivity	It was discovered that as the temperature of the NEPCM was raised, so did its thermal diffusivity.
[147]	Myristic Acid	Differential Scanning Calorimetry (DSC)	Measurement of Heat Flow	During solidification, the cooling rate was discovered to have an effect on the NEPCM's melting temperature and heat of fusion
[148]	Stearic Acid	Hot Disk Transient Plane Source (TPS)	Measurement of Thermal Conductivity	At greater temperatures, the NEPCM's thermal conductivity plateaued after initially rising with temperature
[149]	Eicosane	Laser Flash Technique	Measurement of Thermal Diffusivity	Increasing temperatures were found to increase the NEPCM's thermal diffusivity, with the highest values being recorded in the liquid form.
[150]	Capric Acid	Transient Plane Source (TPS), Differential Scanning Calorimetry (DSC)	Measurement of Thermal Conductivity and Heat Flow	Graphene oxide was added to the NEPCM to improve its thermal conductivity and fusing heat
[151]	Glauber's Salt	Hot Wire Method	Measurement of Thermal Conductivity	At the eutectic composition, the NEPCM displayed the greatest thermal conductivity values of all temperatures tested.
[152]	Polyethylene Glycol (PEG)	Transient Plane Source (TPS),	Measurement of Thermal Conductivity and Specific Heat Capacity	There was a correlation between the PEG content and the NEPCM's thermal conductivity and specific heat capacity
[151]	Glauber's Salt	Differential Scanning Calorimetry (DSC),	Measurement of Heat of Fusion and Thermal Conductivity	By mixing in graphite nanoplatelets, the NEPCM was able to raise both its melting point and thermal conductivity
[153]	Eicosane	Transient Plane Source (TPS)	Measurement of Thermal Conductivity	When both temperature and nanoparticle concentration were raised, the NEPCM's
[154]	Octa-dane	Transient Plane Source (TPS)	Measurement of Thermal Conductivity and Specific Heat Capacity	The NEPCM's thermal conductivity and specific heat capacity change with nanoparticle concentration and temperature.

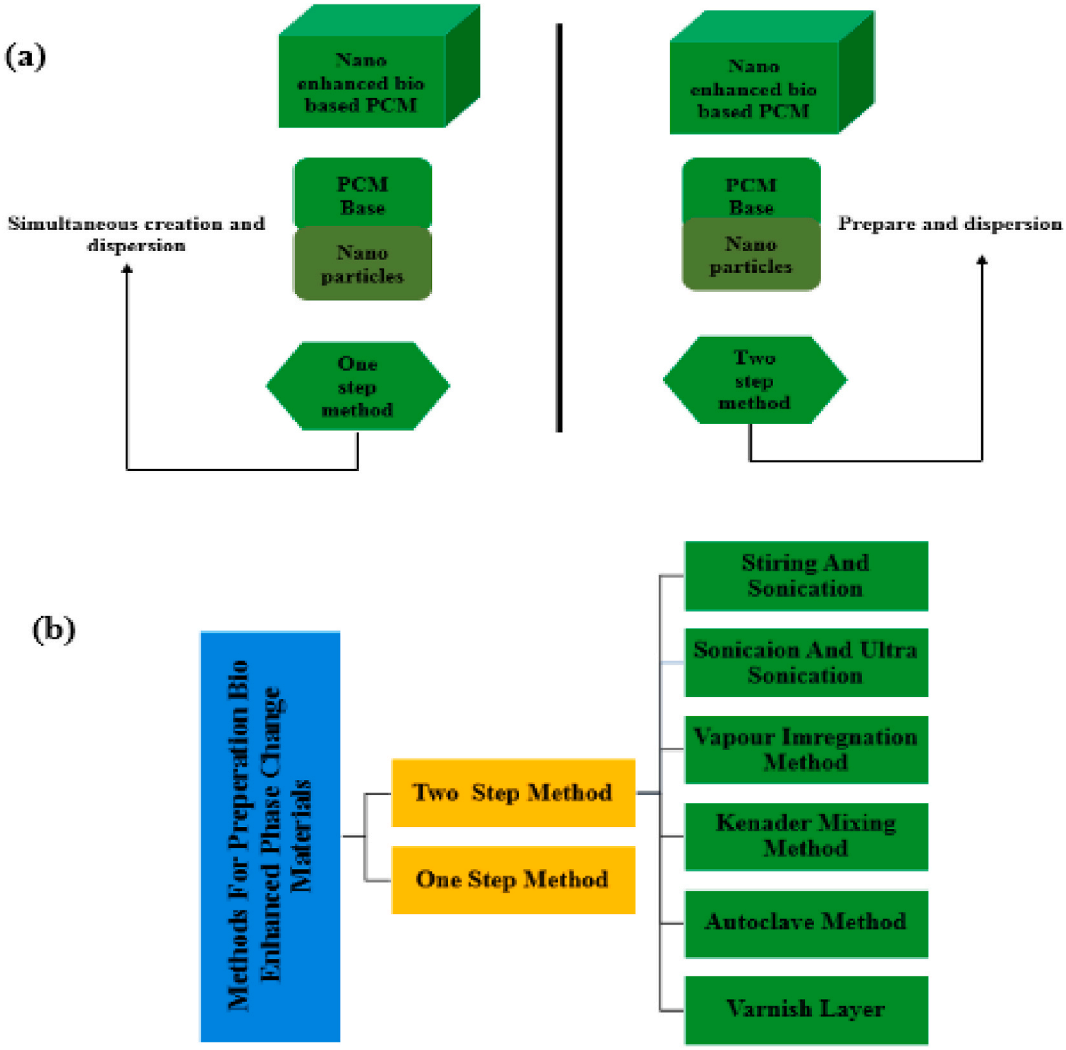

Fig. 11. (a) simultaneous creation and dispersion of nano enhanced bio based PCM (b) Methods for Preparation Bio Enhanced Phase Change Materials.

6.1.1. Stirring and sonication method

A magnetic stirrer is used to vigorously mix the liquid PCM for roughly 1 h after a specific number of nanoparticles have been added. Once everything has been mixed together, it is sonicated continuously at a frequency of 45–65 Hz for around 30 min before being cooled. The temperature obtained during sonication is lower than the PCM melting point. The stirring and sonification process (shown in Fig. 12 a) is illustrated in detail in [123,124].

6.1.2. Ultrasonication and sonication

After a predetermined quantity of nanoparticles has been introduced to the PCM in liquid form, it is sonicated continuously at a frequency of 45–60Hz for approximately 30 min. For 2 h, the NEPCM is placed in an ultrasonic bath to ensure that all of the nanoparticles have been incorporated into the PCM see in Fig. 12(b). The ultrasonication process necessitates a bath temperature over PCM's melting point [125,126]. Shape-stable composite PCMs are widely used in thermal energy storage due to their superior physical, thermal, chemical, energy storage, and energy conversion capabilities. For clarification, this show: Light–, magnetic–, and electrical–thermal. Engineering chemistry advances have made composite PCM manufacture possible on a big scale. Production of composite PCMs in huge quantities made this outcome possible. Because of this, many enclosing tactics [120] have emerged over time. This word encompasses a wide range of packaging methods. These methods include impregnation, microencapsulation, and nanoencapsulation.

6.1.3. Impregnation

A matrix must be fully submerged in a liquid phase change substance to be impregnated. Impregnation might be melted, solution,

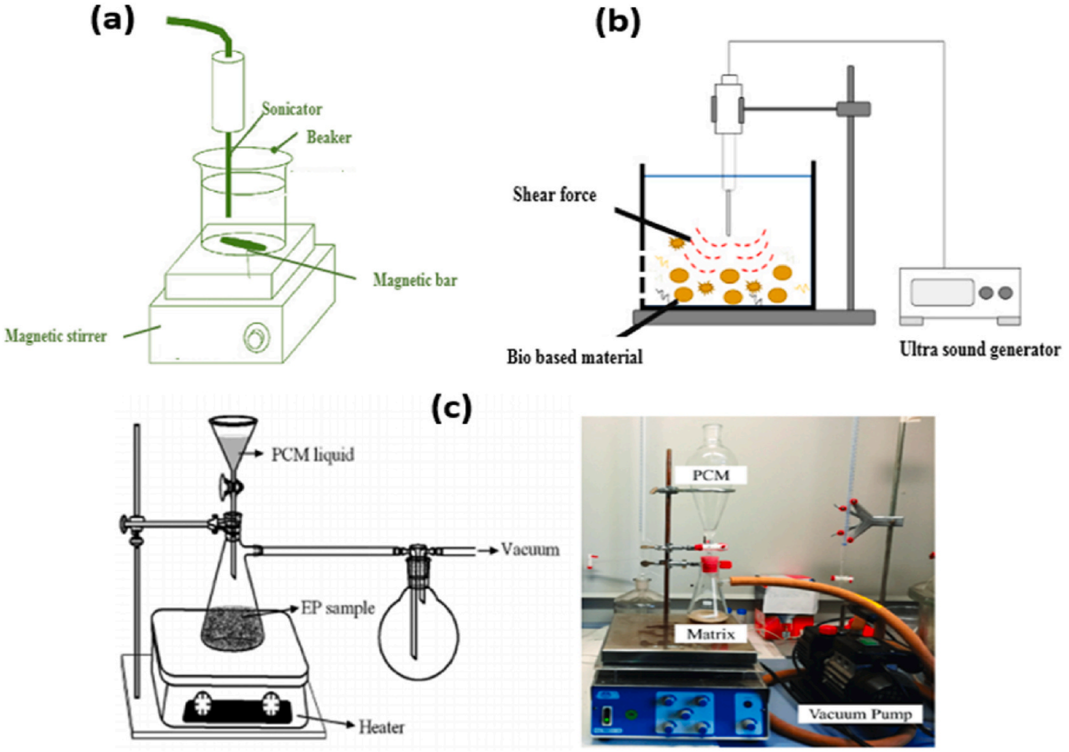

Fig. 12. (a) Stirring and Sonification Process [124], (b) Sonication and ultrasonication method, (c) Vacuum Impregnation [127].

or vacuum, as indicated in Fig. 12 (c). In an electric furnace, solid and porous PCM was heated to create a vacuum. To create an airless space. Heat erythritol to 150 °C and melt it as the second step. After soaking in liquid PCM for 1.8 kg/s, porous materials' pore structures were examined. TheEP was immersed in liquid PCM at 0.6, 1.2, 1.8, and 3.6 kg/s at four temperatures to evaluate impregnation. The vacuum pump was turned off in the fourth step to lower oven pressure. A stainless-steel mesh separated PCM liquid and soaked porous materials. To prevent PCM from being trapped in pores or absorbed by composites, it was held in 150 °C in the furnace. The pieces were then dried. DSC can determine product latent heat and melting point. By employing SEM, product internals could be shown. Several rapid heating and cooling cycles were performed on the EP/erythritol mixture to determine its latent heat.

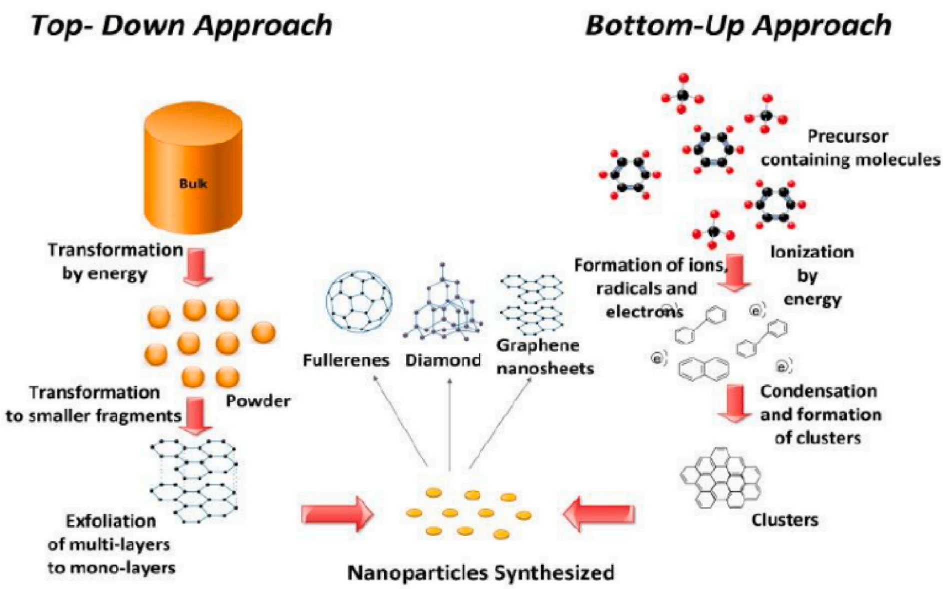

Fig. 13. Top-down or Bottom-up method [130].

6.1.4. Nanoencapsulation

The innovative process of nanoencapsulation is being utilized to encapsulate PCMs in order to prevent leakage, boost thermal strength and heat transmission, and make PCMs more reliable during charging and discharging cycles. Nanoencapsulation is a method for making nano capsules by surrounding a nanoparticle (the "core" or "active") with a matrix (the "shell"), which encloses the nanoparticle. The shell shields the active chemical in its center. The core can be delivered to its destination in a controlled manner, either by diffusion or in response to a trigger (pH, shear, etc.). The duration of this refuge is flexible. Nanomaterials can be created with either a top-down or bottom-up strategy as shown in Fig. 13.

6.1.5. Top-down approach

This method involves the use of specialized equipment that facilitates downsizing and shape for the necessary nanomaterial applications. This strategy employs emulsification and evaporation of emulsification solvent [128].

6.1.6. Bottom-up approach

In this method, materials are synthesized via the self-assembly of molecules under the control of environmental conditions like pH, concentration, temperature, and ionic characteristics. This method encompasses processes including coacervation, nanoprecipitation, and inclusion complexation [129].

6.2. Microencapsulation

PCM materials with a thin polymer coating are used to make micrometer-sized capsules. Inflow, volumetric fluctuations during the melt-freeze phase, and environmental sensitivity are addressed by this approach. The heat transmission surface area increases. Microencapsulation can either be chemical or physical. Industrial applications include chemical and physical processes, but chemical processes have advantages. Physical microencapsulation technologies are cheap and easy to scale up, however they have drawbacks like variable sizes and traits. Chemical procedures offer the appropriate traits and sizes [131]. Chemistry has only two drawbacks: cost and complexity. Microencapsulation Pockets, thin plates, tubes, shells, etc. hold PCM. With PCM, buildings are more practical, offer greater volume control, and safeguard the environment. Because macro encapsulation suffers leakage, poor heat transfer, and thermal stratification, microencapsulation is preferable [132]. In Fig. 14, PCM encapsulation methods are demonstrated.

7. Optimization of properties via deep learning (predicting phase change Material's thermal performance using deep learning)

In particular, research has gravitated toward the data-driven approach to predicting a building's energy performance because of the benefits it provides in terms of reduced computation resource burden, increased speed, and high forecast accuracy [157]. The data-driven approach has led to the use of machine learning (ML) and deep learning (DL) to estimate building thermal performance. How machine learning and deep learning models adjust input data before delivering outputs differs. DL models are considered to undertake numerous input changes before producing outputs, unlike ML models, which typically only loop through inputs once or twice. DL models provide end-to-end learning without feature engineering for increasingly complex patterns [158–161]. To date, the ANN is the simplest DL model that can be used. (ANN). It can simulate the functions of neurons in the brain. Neurons are highly interconnected cells that carry out routine activities on their own but are capable of intricate problem-solving when working together [162]. The importance of ML and DL models in the process of achieving very high levels of energy efficiency in building designs is

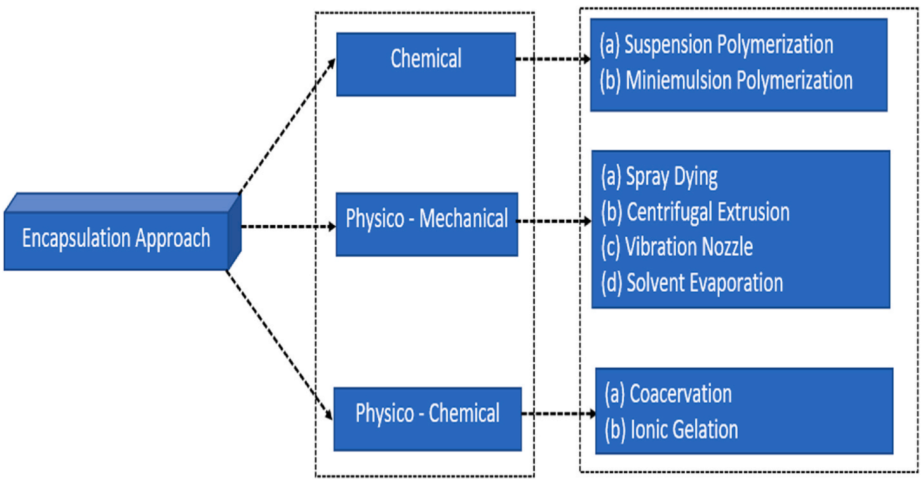

Fig. 14. Encapsulation approaches of different PCM.

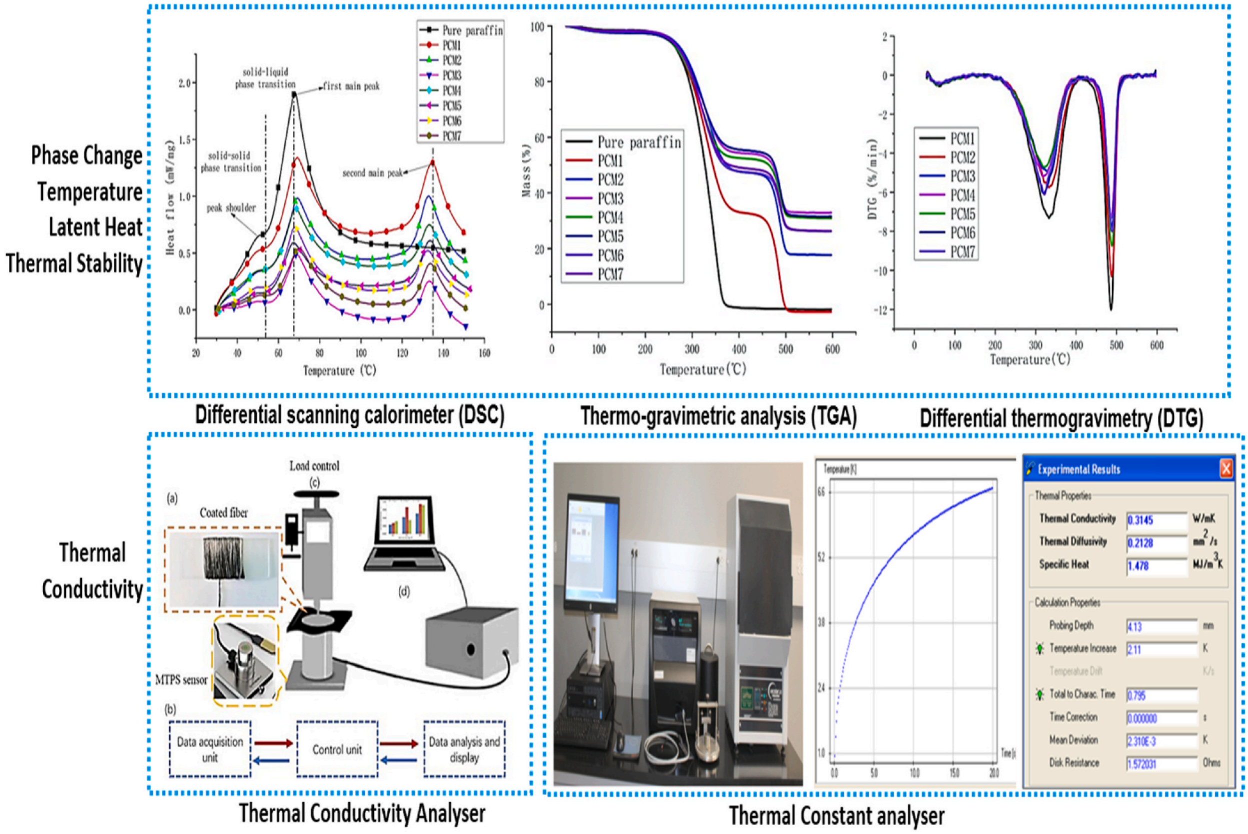

Fig. 15. Various Properties and characterization methods [155,156].

highlighted by Peng et al. [163]. They show how a building's total energy consumption can drop by between 7 and 52 percent when a demand-driven management strategy like the one implemented by the ML model is put into place. Zhou and Zheng [164] used the ML model to create a demand-side controller for tall office buildings. They accounted for the possibility of varying weather. It was found that the peak power consumption of an office building may be drastically reduced by switching to model-based control. Optimizing a building's energy consumption was proposed as a use for ANN-based predictive model management by Reynolds et al. [82,165]. It was found that modest office buildings could see a reduction in their energy consumption of up to 25% through the use of ANN-based predictive model control. Many researchers have put in a lot of time and effort to improve ML and DL model predictions [166–169]. The different studies that fit this description are summarized in Table 1. The studies conducted on various machine learning and deep learning models are summarized in Table 6. According to the literature review above, ML models and ANN are effective at forecasting the performance of thermal systems used in buildings, including energy storage systems with PCM [170], solar collectors with PCM, and centralized PCM storage systems [171]. The only accessible research uses ANN to predict PCM-based building envelope dynamics. This work focused on heat flux projections using ANN in a PCM-embedded building envelope. It also showed major challenges with using the DL model to unobserved test data. The ANN was designed to model and predict surface heat flux for given inputs of surface temperature boundary conditions, but it fared badly on unknown test data [172,173]. Although the ANN was supposed to predict one parameter, this is true. To analyses PCM's dynamic behavior in designing applications with a strong ANN model that improves accuracy and generalization, this article shows many potential development options. Current research lacks strong ML or DL-based models to consistently forecast PCM-integrated building envelope thermal performance [174,175].

7.1. *Machine learning and deep learning model*

In this study, shows various approaches are study in order to forecast the thermal performance of PCM integrated. Deep learning (DL) and machine learning (ML) are as follows.

7.1.1. *Extra trees regression (ETR)*

Another example of a tree-based ensemble machine learning model is the Extra Trees Regression model (ETR). An extension of the random forest technique is this model. This model is also known as the highly randomized forests model in some circles. A subset of features is used by the random forest and additional trees models to randomly select training predictors. However, the random forest model makes use of more features. The most important difference between these two is because RFR employs the split that is the most

Table 6
Summary of literature for various deep learning and machine learning models to predict the dynamic behaviors and thermal conductivity.

Deep Learning Model	Machine Learning Model	System Analyzed	Statement	Ref.
ANN	-	A thermal energy storage system with PCM	ANN models predict heat absorption and emission in a thermal energy storage device during charging and discharging. The model's predictions are confident at 95% and have low uncertainty at 5%.	[170]
ANN	Gaussian, support vector regression (SVR) and linear regression	Space heating and cooling load prediction for residential building	The Gaussian radial basis function kernel SVR model performed best of all. 4% adjusted mean absolute error and root mean-square error.	[171]
ANN	–	Dynamic behavior of building envelope with PCMs	An artificial neural network model is used to forecast the heat flux. Error of the model is on average 0.34 W/m2.	[172]
ANN	–	Latent heat thermal energy storage system	ANN predicts heat stored in the finned tube via phase change material (PCM) better than the numerical model (average absolute mean relative error of 5.58).	[169]
ANN	–	Centralized PCM storage system	A trained ANN predicts storage system exhaust atmospheric temperature. There was a high correlation between ANN prediction and numerical outcome.	[168]]
ANN with Fuzzy Inference System (ANFIS)	Support Vector Machines (SVM)	Thermal energy storage performance of a solar collector with PCM	For the current dataset, the SVM model outperforms other models such as ANN and ANFIS.	[174]
-	Random Forest Regression (RFR), Extreme Gradient Boosting Regression (XGBR)	Incorporating PCMs into cementitious composites	To predict compressive strength, 154 cement-based PCM microcapsule combinations were developed. - The gradient boosting model had the highest R-SQUARE of 0.977, RMSE of 2.419, and MAE of 1.752.	[171]
ANN	Random Forest	Prediction of building energy consumption	With an RMSE of 4.97 compared to RF's 6.10, ANN did slightly better.	[174]
-	Linear Regression (LR), Decision Tree, and K-nearest Neighbor (kNN)	Prediction of building energy consumption	The greatest results are obtained from the Linear Regression (LR) and the Support Vector Regression (SVR) models.	[182]
ANN	Support Vector Machine (SVM), K-nearest Neighbor (kNN)	Prediction of energy consumption for a smart building	When compared to the ANN and the kNN model, the Support Vector Machine model fared better.	[183]

discriminative, whereas the extra trees model chooses the characteristics and their corresponding value for splitting the node [176].

7.1.2. Random forest regression (RFR)

The random forest model is so named because each tree in the model is created using randomized predictors. Bagging, also known as bootstrap aggregation [94], is the method used to pair together all of the decision trees that have been built. Additional information

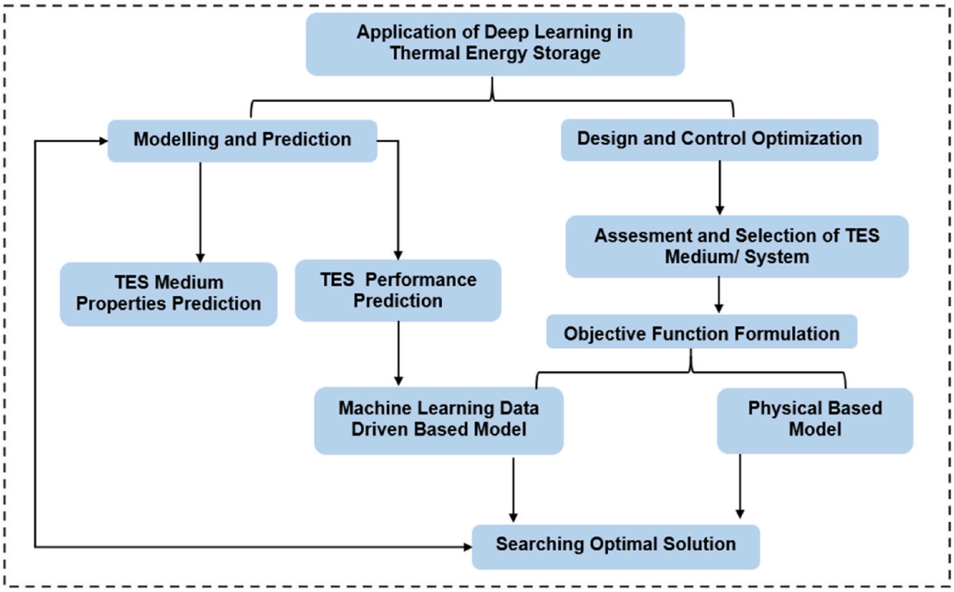

Fig. 16. schematic illustration of application of deep learning and machine learning in thermal energy storage.

on this variant can be found under the reference number [95].

7.1.3. Extreme gradient boosting regression (XGBR)

The ensemble learning method known as XGBR is based on the traditional boosting of the tree in the form of a simple gradient boost [100]. The first-order derivative is used to optimise the loss function in the GBR model, while the Tylor expansion is used in the XGBR model to maximize the loss function. Additionally, XGBR has a regularization mechanism that aids in preventing the model's associated overfitting. There is more information on this variant under the reference number [101].

7.1.4. Gradient boosting regression (GBR)

Boosting is one of the ensembles learning techniques. It was initially developed to solve classification-based problems, but it has since been adapted to solve regression-based models [98]. The power student is created using this strategy by combining the knowledge of several less capable learners. Here, another branch of the learning tree is inserted in the proper order [177].

7.1.5. Cat Boost: gradient boosting with categorical features

The gradient boost algorithm serves as the basis for the implementation of cat boost, which is an organized variant of the boost algorithm. The framework of the Cat Boost model can be found between the symmetrical trees. Within these trees, the same features are utilized to partition the dataset into left and right halves [178].

Fig. 16 shows schematic illustration of application of deep learning and machine learning in thermal energy storage. AI-based prediction models like the support vector machine and artificial neural network may reliably and quickly anticipate TES performance and material properties, according to research. AI techniques are beneficial and promising for energy storage, including performance modelling, system control and operation, system design and evaluation, especially when external parameters interfere or cost and energy savings are important [178]. Unfortunately, the TES database is insufficient to support AI-integrated TES. AI-integrated TES research should represent future energy system characteristics. ML and AI with physics-based concepts may optimise design and anticipate performance quickly, used ML to anticipate the time remaining to reach a pre-set melt fraction for PCMs during melting. They tested an ML-based ANN technique for training data efficacy and reliability is shown in Table 6. They wanted to improve the ANN model's predictability for calculating time to attain the objective [179–181].

8. Conclusion

Biodegradable waste-derived phase change materials (PCMs) can increase the energy efficiency and sustainability of thermal energy storage systems. Biodegradable waste-based heat transfer fluids and biopolymeric frameworks for PCMs are evaluated in this paper. The primary objectives are to characterise and integrate novel PCMs, improve system performance, and evaluate the economics of energy efficiency techniques. For their high latent heat storage capacity and thermal stability, paraffin, fatty acids, and polyethylene glycol are being studied extensively. The study looks on multifunctional biomass-based composite phase transition materials for energy storage. In thermal energy storage system applications, biodegradable waste PCMs can reduce fossil fuel dependence and greenhouse gas emissions. Biodegradable heat transfer fluid is used in thermal energy storage. Mechanical design and pumping losses support direct contact PCM thermal storage. PCMs regulate energy. Because of their high latent heat storage capacity, wide temperature range (−5 °C–190 °C), thermal stability through 100 heating-cooling cycles, and other properties, paraffin, fatty acid, and polyethylene glycol are being investigated. The thermal conductivity of the building envelope is increased by latent heat storage. For edible-oil-free PCMs, waste heating oil and non-edible plant oils should be used and provide the thermodynamic study of a new operational split SRT PCM thermal storage system. Thermal assessments connect energy-efficient system designs to heat, glass transition temperatures, conductivity, and heat exchanger conductance. Organic and inorganic PCMs are both commonly used. Organic PCMs are compatible with the vast majority of regularly used construction materials, whereas inorganic PCMs are non-corrosive, chemically inert, and exhibit little or no subcooling. Bio-based PCMs (BPCMs) are non-hazardous to deal with and have high thermal and chemical stability. They are also non-corrosive, with a high latent heat of fusion and a suitable melting temperature. Predictive models for thermal energy storage devices show that artificial neural network (ANN) models perform differently. The Gaussian radial basis function kernel Support Vector Regression (SVR) model captured heat-related charging and discharging complications with a 4% adjusted mean absolute error. The ANN model predicted heat flux better than the numerical model and finned tube heat better. SVM models outperformed ANN and ANFIS in some datasets. Material property predictions favored the gradient boosting model, however Linear Regression and SVR models performed better, emphasizing the relevance of application and dataset-specific model selection.

This article critically analyzes the utilization of biodegradable waste-derived phase change materials (PCMs) for thermal energy storage systems, emphasizing the prediction of their thermal conductivity through machine learning (ML) and deep learning (DL) techniques. The study underscores the importance of sustainable energy solutions amid concerns about fossil fuel usage and non-renewable energy sources. It explores the potential benefits of biodegradable waste-based PCMs, including reduced reliance on fossil fuels and lower greenhouse gas emissions. The integration of nanotechnology to enhance thermal conductivity and the application of predictive models for understanding complex thermal performance in building structures are discussed. Sustainability aspects, such as reduced carbon footprint, waste reduction, and circular economy alignment, are highlighted in the context of biodegradable waste-based PCMs. The article concludes by emphasizing the promising role of these PCMs in achieving energy-efficient thermal storage systems and advocates for further research in areas like biobased PCM selection criteria, environmental impact assessments, and system optimization using ML and DL techniques. Overall, the paper provides a comprehensive overview of the potential of biodegradable waste-derived PCMs in promoting sustainability and advancing energy-efficient solutions in the built environment.

Future scope

- A comprehensive database governing existing biobased PCMs, their characteristics, and accompanying environmental data is desperately needed.
- Due to a lack of environmental data relevant to each PCM and a lack of comparisons with traditional energy storage technologies, life cycle assessments (LCAs) of biobased PCMs have not yet been able to draw clear conclusions about their environmental implications.
- More research on the biodegradability and compatibility of biobased PCMs with other components of thermal energy storage (TES) systems is required, and there is a scarcity of publications that address and characterise biobased PCMs after extensive testing in operational environments (end-of-life characterization).
- Bio-based PCM functionalization must be systematised, and the environmental impact of enhancement materials must be considered in addition to the benefits of increased material performance.

CRediT authorship contribution statement

Aman Sharma: Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Pradeep Kumar Singh:** Writing – review & editing, Validation, Supervision. **Emad Makki:** Visualization, Supervision. **Jayant Giri:** Validation, Supervision. **T. Sathish:** Visualization, Validation.

Declaration of competing interest

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

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