Unveiling the Promise of Phase Change Materials (PCMs) in Geopolymer Composites-Comprehensive Review

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Abstract

This review delves into the application of bio-based phase change materials (PCMs) within geopolymer matrices, with a specific focus on their environmental advantages. Geopolymers, renowned for their eco-friendly characteristics as substitutes for conventional cement-based materials, have attracted considerable attention. The review covers topics such as geopolymer technology, bio-based PCMs, recent advancements, emerging trends and the existing challenges in upscaling, durability, and standardization when integrating bio-based PCMs into geopolymer matrices. In conclusion, this review represents a valuable resource for individuals dedicated to promoting environmental sustainability in the realms of construction and materials. Bio-based geopolymer composites incorporating PCMs are poised to play a pivotal role in the pursuit of more environmentally friendly and energy-efficient building materials.

Keywords Bio PCM, Conventional PCM, Environmental sustainability, Geopolymer as potential template, Trends, Developments, Challenges, Future directions

Graphical abstract

1.Introduction

The continuous release of carbon dioxide (CO2) and the high energy demands associated with the production of Ordinary Portland Cement (OPC) are contributing to ongoing ozone layer depletion and global warming. However, the adoption of geopolymer concrete (GPC) technology in the construction sector is promoting sustainable development and a cleaner environment by reducing environmental pollution (Alhassan et al., 2023; Kanagaraj et al., 2023). Geopolymers are advanced materials known for their eco-friendly properties and versatile applications. They are inorganic, amorphous, three-dimensional aluminosilicate networks formed through a process called geopolymerization. This process involves dissolving silicon (Si) and aluminium (Al) atoms from source materials and reorganizing precursor elements, resulting in a newly synthesized solid structure (Alhassan et al., 2023; Imtiaz et al., 2020; Kanagaraj et al., 2023; Mehrizi et al., 2023). Common aluminosilicate source materials for geopolymers include clays and clay minerals, such as kaolin, kaolinite, metakaolinite, calcined clay, and zeolite. In the context of sustainability as a substitute for Ordinary Portland Cement (OPC) composites, Geopolymer Concrete (GPC) has demonstrated remarkable strength and durability (Amran et al., 2021; L. Assi et al., 2018; L. N. Assi et al., 2020; Festus et al., 2022; G. Xu & Shi, 2018; Yu et al., 2014).

Energy and its economic implications are crucial for a nation's economic well-being. Achieving self-sufficiency in energy supply and demand can undoubtedly boost a country's economy. Among the sectors with significant energy consumption, buildings rank third, following the transport and industrial sectors (Alva et al., 2018). Buildings allocate a considerable portion of their energy use to HVAC (Heating, Ventilation, and Air Conditioning) systems, primarily for ensuring occupant and equipment comfort. The utilization of energy storage systems provides an effective way to bridge the gap between energy supply and demand (Abdallah et al., 2016; Ahmed, 2014).

One such energy storage system is Latent Heat Thermal Energy Storage (LHTES) employing Phase Change Materials (PCMs). These systems are widely used in various domains, including solar thermal power plants, nuclear power facilities, and building thermal management, thanks to their isothermal properties, substantial thermal energy storage (TES) capacity, and phase change occurring within a narrow temperature range. Unlike power generation facilities, buildings using Phase Change Materials (PCMs) can store surplus solar energy during the day, reducing heat ingress into the building, and releasing it at night when temperatures drop below the PCM's melting point, making PCMs promising for thermal management in buildings (Arivazhagan et al., 2020; Sharshir et al., 2023).

Phase Change Materials (PCMs) are substances that can absorb and release substantial amounts of energy during phase transitions, depending on their specific temperature range and threshold values. To fully harness PCM capabilities, certain criteria related to thermal, physical, chemical, and kinetic attributes must be met, alongside economic feasibility and material availability. Essential chemical requirements for PCMs include non-toxicity, non-flammability, and low risk of explosion (Navarro et al., 2019; A. Sharma et al., 2009).

Common materials used in Latent Heat Thermal Energy Storage (LHTES) include paraffin waxes, salt hydrates, and eutectic compositions, which can be organic-organic, inorganic-inorganic, or organic-inorganic. Fatty acids are also frequently employed. The challenge now is to identify the optimal bio-based Phase Change Material (PCM) or bio-composite PCM that is cost-effective, practical, and environmentally friendly, particularly for building applications(Saxena et al., 2019).

Recent research has shown increasing interest in using bio-based Phase Change Materials (PCMs) in Latent Heat Thermal Energy Storage (LHTES) within buildings due to their cost-effectiveness, renewability, non-toxicity, wide availability, and accessibility (de Albuquerque Landi et al., 2020).

The main objective of this research is to provide an overview of the key elements to be discussed in subsequent sections. It begins by addressing the environmental imperatives driving the need for sustainable construction materials and then delves into the principles of geopolymer technology with a focus on its eco-friendly features. It introduces the concept of biobased PCMs and their unique qualities that enhance the environmental sustainability of geopolymer matrices. This field is interdisciplinary, where materials science, engineering, and environmental sustainability intersect, offering a compelling case for bridging sustainability and technological innovation to reshape the construction and materials industry.

In the following sections of this review, we will explore the latest developments, innovative material synthesis approaches, PCM encapsulation techniques, and manufacturing methods. Emerging trends, such as the use of waste materials, nanotechnology applications, and sustainable supply chain management, will be discussed in the context of biobased geopolymer composites. Further, subsequent paragraphs, will also addresses the persistent challenges faced by researchers and industries when adopting biobased PCMs in geopolymer matrices, including scalability, durability, cost-effectiveness, and standardization. This review aims to be a valuable resource for researchers, practitioners, and policymakers with a common goal of advancing environmental sustainability in the construction and materials industry. The pursuit of greener, more energy-efficient building materials remains essential, and biobased geopolymer composites infused with phase change materials are poised to play a crucial role in this endeavour.

2.Exploring porous geopolymer as Potential Template for Phase Change Materials

In the quest for sustainable and energy-efficient building materials, the incorporation of phase change materials (PCMs) has emerged as a promising strategy. PCMs have the ability to store and release thermal energy during phase transitions, thereby contributing to improved energy efficiency in various applications, including building and construction. To maximize the effectiveness of PCMs, their encapsulation within suitable matrices is essential. One such matrix with considerable potential is porous geopolymer. This study aims to explore the feasibility of porous geopolymer as a template for phase change materials. Geopolymers, known for their low carbon footprint and remarkable durability, present an environmentally friendly alternative to traditional cementitious materials (Ji et al., 2022; Laasri et al., 2022).

The introduction of porosity into geopolymer matrices opens up new possibilities, particularly when it comes to housing PCMs, making them a viable candidate for thermal energy storage in buildings (Gencel et al., 2022).

2.1 Properties and advantages of geopolymers as a matrix material for PCM storage

Geopolymers have exceptional thermal stability, making them an ideal choice for encapsulating phase change materials (PCMs) (Asefi et al., 2022). This property ensures that the geopolymer matrix can withstand the repeated thermal cycles associated with PCM phase changes, which is crucial for the long-term durability and reliability of PCM storage systems (Tyagi et al., 2022). Geopolymers can be used in various applications such as residential heating or cooling, industrial processes, and renewable energy systems (Feng et al., 2022). The use of geopolymer matrices provides a stable environment for PCMs, allowing them to efficiently store and release thermal energy (Gao et al., 2021). This combination of geopolymer and PCM offers a promising solution for energy storage and management, contributing to the development of sustainable and efficient building materials and systems (Degefu et al., 2021).

One of the significant advantages of geopolymers is their flexibility to be engineered with tailored thermal conductivities. The ability to customize the thermal conductivity of the geopolymer matrix allows for precise control over heat transfer within the PCM storage system. Effective heat transfer between the PCM and its surroundings is essential for efficient energy storage and release, ensuring optimal system performance (Aziz et al., 2019; Fiala et al., 2019). Geopolymers have been found to exhibit high thermal stability and low thermal conductivity, making them suitable for thermal energy storage applications. Additionally, the addition of electrically conductive carbon black admixture to geopolymers has been shown to enhance their electrical properties, which can further improve heat evolution and distribution within the material (Parhizi & Jain, 2019; Sabbatini et al., 2017). Experimental studies have also been conducted to analyse the thermal resistance and dilatometry of geopolymer formulations, providing insights into the critical parameters that influence their properties (Wołoszyn et al., 2021).

Geopolymers exhibit remarkable resistance to various chemical agents. Chemical property is indeed crucial for PCM storage systems, as it ensures compatibility with the PCM material and other components within the system, contributing to long-term stability and functionality. The chemical resistance of PCMs is an important factor in their thermal stability and reliability. The review of different PCMs for heat storage applications discusses their thermal stability and reliability, including organic, inorganic, eutectic, and composite materials (Madeswaran et al., 2021; Munir & Hussain, 2022; Tyagi et al., 2022). Additionally, the life cycle assessment (LCA) and life cycle inventory (LCI) analysis of PCMs provide information on their material and energy requirements, as well as their environmental impact. The selection of suitable PCMs for thermal energy storage is based on their physical and chemical properties, as well as their state and melting temperatures. Therefore, considering the chemical properties of PCMs is essential for ensuring the long-term stability and performance of PCM storage systems (Sawadogo et al., 2021; Yousefi et al., 2021).

Geopolymers possess excellent adhesion properties, allowing them to securely hold the PCM in place and enhance the overall performance and reliability of the system. The geopolymer matrix's ability to prevent phase separation or leakage is a key advantage when integrating geopolymers into various applications (Abulencia et al., 2021; Chen et al., 2022; Chu & Kong, 2021; Díaz & Barrios, 2022).

Geopolymers can be formulated with different compositions, allowing for the customization of their properties to match specific PCM requirements. This includes tailoring the melting and freezing temperatures of the PCM to align with the desired application (Tyagi et al., 2022; Wan et al., 2021). Geopolymers typically have low densities, which can be advantageous for PCM storage applications. Lightweight PCM storage systems can be particularly valuable in construction or transportation applications (Sawadogo et al., 2021).

Geopolymers are crucial in minimizing phase separation issues between the PCM and the matrix material during the phase change process, ensuring consistent and reliable thermal performance. They can be engineered to have good heat transfer properties, promoting efficient heat exchange between the PCM and its surroundings. Geopolymer-based PCM storage systems facilitate rapid charging and discharging of thermal energy, making them highly effective in managing temperature variations. Geopolymers are known for their long-term durability, contributing to the extended operational life of PCM storage systems. This durability ensures that the PCM storage system remains effective and reliable over time, leading to energy savings and sustainability (Degefu et al., 2021; Jiang et al., 2021; Q. Jin et al., 2022; Regin et al., 2008; Tyagi et al., 2022).

Geopolymer-based PCM storage systems can be designed and produced at various scales, from small residential applications to large district-level heating and cooling systems. This scalability makes geopolymer matrices suitable for a wide range of applications, enhancing energy efficiency and sustainability across different sectors (Abulencia et al., 2021; Shao et al., 2021). Geopolymers offer a compelling combination of properties and advantages, including thermal stability, tailored thermal conductivity, chemical resistance, adhesion, customizability, low density, phase separation minimization, enhanced heat transfer, durability, low environmental impact, and scalability. These attributes make geopolymer-based PCM storage systems a promising solution for a variety of applications, contributing to energy efficiency and sustainability goals.

2.2 Methods of geopolymer synthesis and characterization

The processes of synthesizing and characterizing geopolymers are pivotal steps in harnessing their full potential for various applications, including construction, infrastructure, and advanced materials. In this discussion, we will explore the common methods employed for geopolymer synthesis and the techniques used for characterizing these materials.

2.2.1. Geopolymer Synthesis

Geopolymers can be synthesized using different methods. The most widely used method is alkaline activation, which involves mixing a reactive aluminosilicate precursor with an alkaline activator solution. This process forms a three-dimensional geopolymer network through a polycondensation reaction. Another method is the sol-gel process, where a geopolymer precursor solution is prepared by hydrolysing and condensing alkoxysilanes or organo-silanes. This solution is allowed to gel and harden, resulting in the formation of a geopolymer matrix. Geopolymers can also be synthesized by blending different precursor materials, such as metakaolin, fly ash, and slag. This blending approach allows for the optimization of geopolymer characteristics for specific purposes (Güngör & Özen, 2021; Krishna et al., 2021; Kushwah et al., 2021).

2.2.2. Characterization

X-ray Diffraction (XRD) is a fundamental technique used to analyse the crystalline structure of geopolymers, identify mineral phases, and determine the degree of amorphousness, which influences material properties. Fourier Transform Infrared Spectroscopy (FTIR) is employed to investigate the chemical bonding and functional groups within geopolymers, providing insights into their structure and composition. Scanning Electron Microscopy (SEM) allows for the observation of the microstructure and morphology of geopolymers, providing information on particle distribution, porosity, and interfacial characteristics. Thermal Analysis (TG-DTA) techniques, such as thermogravimetry (TG) and differential thermal analysis (DTA), assess the thermal stability and decomposition behavior of geopolymers, especially for high-temperature applications. Mechanical testing, including compressive strength, flexural strength, and modulus of elasticity, is essential for assessing the suitability of geopolymers for structural applications. Porosity analysis is crucial for understanding the permeability and durability of geopolymers, particularly in construction materials, by evaluating pore size distribution and specific surface area. Nuclear Magnetic Resonance (NMR) techniques, such as solid-state NMR, provide insights into the atomic-level structure and dynamics of geopolymers, contributing to a comprehensive understanding of their properties (Azam et al., 2022; Meng et al., 2021; Richard et al., 2022).

The synthesis and characterization of geopolymers are complex processes that necessitate a combination of techniques to tailor their properties for specific applications. These methods, in conjunction with ongoing research and development, continue to enhance the role of geopolymers as sustainable and high-performance alternatives in the construction and materials industry.

2.3 Role of geopolymers in enhancing the thermal performance of PCM composites

Geopolymers play a significant role in enhancing the thermal performance of Phase Change Material (PCM) composites, which are materials designed to store and release thermal energy during phase transitions. This combination offers several advantages for various applications, particularly in the field of energy-efficient building materials and thermal energy storage systems.

Geopolymers can be tailored to have low thermal conductivity, which is crucial for maintaining the efficiency of PCM composites by minimizing heat loss and gain (Alves et al., 2023; Jia et al., 2020; Raut et al., 2023). Geopolymers have been found to have lower thermal conductivity compared to traditional bricks, making them suitable for thermally efficient building materials. In addition, the use of light geopolymers in cladding panels for facades has shown an increase in thermal resistance, indicating their effectiveness as thermal control materials. Geopolymers also have excellent heat resistance and can be converted into ceramic materials with controllable thermal properties, making them promising precursors for high-temperature applications (Matsimbe et al., 2022).

Geopolymer-based PCM composites have been shown to effectively store and release thermal energy over a range of temperatures, making them ideal for applications such as solar energy storage. These composites have been developed using different materials and techniques. For example, one study used hierarchically porous kaolinite-based geopolymer (PKG) embedded with polyethylene glycol 4000 (PEG4000) to create shape-stabilized composite PCMs with high thermal energy storage properties (H. Zhang et al., 2023). Another study employed artificial geopolymer aggregate (GPA) as a novel PCM carrier, achieving excellent mechanical strength and thermal conductivity. Additionally, a PCM composite was designed using a combination of metal-organic frameworks (MOFs) and expanded graphite (EG), resulting in enhanced thermal conductivity and shape stability. Furthermore, geopolymer-based concrete (GEO) has been found to withstand high temperatures and exhibit higher thermal storage capacity compared to ordinary Portland cement (OPC)-based materials. Overall, these studies demonstrate the potential of geopolymer-based PCM composites for efficient thermal energy storage in various applications, including solar energy storage(Fang et al., 2023; Rahjoo et al., 2022; Xiao et al., 2023).

3.Biobased Phase Change Materials

Biobased Phase Change Materials (PCMs) represent an innovative class of materials with significant potential in various applications, particularly in the fields of energy efficiency and thermal management. These materials undergo phase transitions, absorbing or releasing latent heat, which makes them crucial for storing and managing thermal energy. Biobased PCMs, as the name suggests, are derived from renewable, biological sources, setting them apart from traditional PCMs that often use non-renewable resources. This environmentally conscious approach aligns with the growing emphasis on sustainability and reducing the carbon footprint of various industries.

3.1 Classification and Selection Criteria for Biobased PCMs

When considering biobased PCMs, it is essential to classify them and establish selection criteria to identify the most suitable materials for specific applications. The classification of biobased PCMs can be based on various factors, including their source, phase transition temperature, and chemical composition.

Biobased PCMs can be derived from plant-based, animal-based, or microbial sources. Plant-based PCMs are derived from crops such as soybeans, palm, or corn starch, while animal-based PCMs come from sources like beeswax or tallow. Microbial PCMs are produced through microbial fermentation processes using microorganisms like bacteria or yeast. The phase transition temperature of biobased PCMs determines their suitability for different applications. Low-temperature biobased PCMs are suitable for applications in the range of -20°C to 0°C, while medium-temperature PCMs are ideal for applications between 0°C to 50°C. High-temperature biobased PCMs are designed for applications exceeding 50°C. The chemical composition of biobased PCMs includes fatty acids, such as triglycerides found in vegetable oils, alcohols like erythritol or xylitol, and sugar alcohols like mannitol and sorbitol derived from plant sources (Kang et al., 2015; Ma et al., 2012; Rasta & Suamir, 2019; Yu et al., 2014).

3.2 Environmental benefits and sustainability aspects of biobased PCMs

Phase change materials are substances that can absorb and release a significant amount of thermal energy when they change from one phase (usually solid) to another (usually liquid) at a specific temperature. This property makes them useful for thermal energy storage applications, such as in buildings, solar energy systems, and electronics cooling. Fatty acids, which are organic compounds composed of long hydrocarbon chains with a carboxyl group (-

COOH) at one end, can exhibit phase change behavior under specific conditions(Cellat et al., 2015). In prior scientific literature, fatty acids with melting points falling within the thermal comfort range were identified as capric acid (CA), lauric acid (LA), myristic acid (MA), and palmitic acid (PA). Table 1 was compiled for the purpose of customizing the phase change material (PCM) to meet specific property requirements. The objective of evaluating various binary combinations is to pinpoint a composition that exhibits a narrow and desirable melting temperature range(de Jong et al., 2012). Fatty acids, owing to their notably reduced flammability and origins derived from non-fossil fuel sources, render them better suited for sustainable building applications when compared to paraffins. The thermogravimetric analysis (TGA) data from prior research investigations demonstrates the capability of these mixtures to endure temperatures as high as 120 °C without experiencing decomposition. This observation underscores the potential utility of the phase change materials (PCMs) for passive solar energy storage applications within building structures (Cellat et al., 2015).

Bio-based PCMs represent a sustainable evolution of traditional PCMs. They are derived from renewable sources, including plant oils and fatty acids, making them environmentally friendly alternatives. The utilization of bio-based PCMs reduces the reliance on fossil fuels, decreases carbon emissions associated with PCM production, and supports the transition to a more sustainable energy landscape. Multiple research investigations have illustrated the favourable suitability of employing bio-based Phase Change Materials (PCMs) for Latent Heat Thermal Energy Storage (LHTES) in building applications. This preference is primarily attributed to the economic viability, renewable nature, non-toxic properties, and ready availability and accessibility of these substances(de Albuquerque Landi et al., 2020; Mehrizi et al., 2023).

Untreated fats and vegetable oils exhibit beneficial phase change characteristics that render them suitable for Latent Heat Thermal Energy Storage in building applications, presenting a potential biomaterial replacement for paraffin and salt hydrates. In a previous research publication, an investigation was conducted into the thermal and physico-chemical properties of composite PCMs exclusively composed of bio-based constituents, each with distinct melting points. Specifically, unprocessed coconut fat and natural Palm Kernel vegetable fat were employed as the bio-based PCMs in their native states (Boussaba et al., 2019; Suppes et al., 2003).

Previous research has examined the dynamic thermal behavior of insulation materials enhanced by incorporating bio-based Phase Change Materials (PCMs). Additionally, investigations have assessed the thermal performance of a composite material comprising Boron Nitride and a bio-based PCM with a melting point of 29.38°C. Furthermore, research has explored the thermal and mechanical properties of composites featuring bio-based PCMs (Hu & Yu, 2014; Jeong et al., 2014).

Earlier studies have also demonstrated that unmodified natural fats and vegetable oils possess valuable phase change characteristics suitable for Latent Heat Thermal Energy Storage (LHTES) in buildings. This suggests their potential as viable biomaterial alternatives to conventional options like paraffin and salt hydrates. Moreover, prior scholarly investigations have scrutinized the thermal and physicochemical properties of bio-based Phase Change Materials (PCMs) with melting points of 26.53°C and 22.63°C, respectively. These composites were exclusively composed of bio-based PCMs, with coconut fat and Palm Kernel vegetable fat in their natural states serving as the PCM constituents(Boussaba et al., 2018; Jeong et al., 2014).

3.3 Methods for incorporating biobased PCMs into geopolymers

Incorporating biobased Phase Change Materials (PCMs) into geopolymers involves a carefully planned process to create composite materials with enhanced thermal properties. Geopolymers, known for their versatility and environmental benefits, can be an excellent matrix for the integration of biobased PCMs. When incorporating biobased PCMs into geopolymers, it's essential to consider factors such as PCM loading, compatibility, and the intended application. Proper mixing, dispersion, and curing conditions are critical to achieving the desired thermal performance and long-term stability of the resulting composite materials. Each method has its advantages and may be more suitable for specific applications based on the required properties of the final product.

3.3.1 Encapsulation technique

Phase Change Materials (PCMs) and bio-based Phase Change Materials (bio-PCMs) encapsulation both involve the process of encapsulating materials that undergo phase transitions to enhance their performance in various applications, but they differ primarily in the source and nature of the PCM used. The scientific literature presents a wide array of methodologies for the fabrication of Microencapsulated Phase Change Materials (MPCM). The selection of a particular approach is contingent upon the intended application. Nevertheless, the overarching goal remains unchanged: to prevent the escape of molten PCM while concurrently augmenting the thermal and mechanical properties of the MPCM. These methodologies can be broadly categorized into three principal production techniques: physico-mechanical, chemical, and physio-chemical methods.

Encapsulation serves as a conventional strategy employed for the purposes of PCM containment, ameliorating heat transfer efficiency, and enhancing mechanical durability. These encapsulation methods can be categorized into macroencapsulation and microencapsulation, as well as matrix encapsulation, each characterized by notable disparities in cost and intended applications. Emulsion-templated materials or encapsulation matrices are composed of polymeric structures derived from emulsions(Silverstein, 2017). Porous matrices offer versatile opportunities for the inclusion of diverse materials, including Phase Change Materials (PCMs). In contrast to the conventional spherical encapsulation method frequently applied to non-renewable source-based PCMs, an innovative approach involved encapsulating soybean wax PCM within electro-spun fibers that were shielded by a protective polyurethane layer. This encapsulation process yielded PCMs with commendable thermal stability and robust thermal resistance, thereby warranting consideration for applications in thermal storage and thermal shielding (Hu & Yu, 2012).

Microencapsulation of a Phase Change Material derived from coconut oil, possessing a melting enthalpy of 119 J/g, was accomplished using the method of suspension polymerization, employing stearyl methacrylate and hydroxyethyl methacrylate as key components.

Numerous experimental and computational investigations have been conducted to augment the thermal conductivity, diminish thermal resistances, and mitigate supercooling within biobased Phase Change Materials (PCMs) by introducing highly conductive elements, such as diverse nanomaterials. These investigations encompass techniques such as the dispersion of carbon nanotubes and graphite nanoplatelets within biobased PCMs, leading to a remarkable 375% enhancement in thermal conductivity. Furthermore, research has explored the utilization of graphite nanoplatelets in conjunction with fumed silica for lightweight applications within architectural structures (Jeong et al., 2013; Kang et al., 2015).

3.3.2 Shape stabilization technique

To date, several techniques have been documented for the fabrication of shape-stabilized composite Phase Change Materials (PCMs). These methods encompass microcapsule technology, porous inorganic carrier utilization, the sol-gel approach, and the melt-blending method[58c]. Conventional porous inorganic carriers, such as expanded graphite, diatomite, and expanded vermiculite, exhibit exceptional thermal and physical characteristics.

Nevertheless, there remains potential for further enhancement in the specific capacity of the aforementioned carriers (Novais et al., 2020). Hierarchically porous materials, characterized by the presence of pores with varying sizes and exceptional interconnectivity, have demonstrated exceptional absorption capabilities. Hierarchically porous materials, distinguished by their diverse pore size distribution and remarkable interconnectivity, have exhibited outstanding absorption capabilities. Furthermore, in similar applications, several studies have documented the development of hierarchically porous geopolymers (Gao et al., 2020). Organic Phase Change Materials (PCMs) are known to have inherent limitations, including low thermal conductivity and the potential for leakage during phase transitions. To address these drawbacks, supplementary materials are introduced into the PCM matrix. These additional materials fall into two categories: porous materials, which serve to prevent PCM leakage, and nanomaterials, which enhance the thermal properties of the PCM. When the PCM is combined with both of these supporting materials, it forms a composite known as Shape-Stabilized Composite PCM (ss-CPCM) or Shape-Stabilized PCM(Rathore & Shukla, 2021).

Porous materials facilitate PCM support owing to their augmented surface area, elevated thermal conductivity, and superior chemical compatibility (Huang et al., 2019).

4.Environmental Sustainability:

Bio-based PCMs represent a sustainable evolution of traditional PCMs. They are derived from renewable sources, including plant oils and fatty acids, making them environmentally friendly alternatives. The utilization of bio-based PCMs reduces the reliance on fossil fuels, decreases carbon emissions associated with PCM production, and supports the transition to a more sustainable energy landscape[30c]. Multiple research investigations have illustrated the favourable suitability of employing bio-based Phase Change Materials (PCMs) for Latent Heat Thermal Energy Storage (LHTES) in building applications. This preference is primarily attributed to the economic viability, renewable nature, non-toxic properties, and ready availability and accessibility of these substances (de Albuquerque Landi et al., 2020).

Earlier studies have addressed the assessment of the embodied carbon footprint associated with the production of artificial geopolymer aggregates (GPAs) using varying mix proportions. Additionally, the literature includes data on the embodied carbon content of alternative lightweight aggregates previously reported as carriers for Phase Change Materials (PCMs). These aggregates encompass expanded perlite, synthetic zeolite, expanded foam glass, ceramic foam, and expanded clay (Hammond & Jones, 2011; Tobarameekul & Worathanakul, 2021; Zimele et al., 2019). The objective is to facilitate comparative analysis.

Furthermore, considering an emission factor of 0.231 kgCO2e/kWh for energy consumption [6e], the carbon emissions resulting from the curing process were quantified, yielding a value of 0.164 kgCO2e/kg. While the carbon emissions associated with the curing process alone exceeded the embodied carbon content of the raw materials, it's noteworthy that this energy demand can potentially be offset by utilizing biomethane, biofuel, and waste heat steam sourced from wet waste plants and waste incineration facilities. Furthermore, this accelerated curing methodology holds the potential to enhance aggregate strength and quality while expediting production efficiency, thereby delivering additional economic and environmental advantages.

The utilization of artificial aggregates is driven by a multifaceted objective, aiming to simultaneously address three critical challenges: (1) the repurposing of industrial solid wastes, such as fly ash, red mud, glass waste, and calcium carbide residue, (2) the containment of hazardous waste materials, such as incineration bottom ash (IBA), and (3) the mitigation of natural aggregate depletion. This strategic deployment of various waste materials within artificial geopolymer aggregates (GPAs) has the potential to yield cost savings in waste treatment processes. Beyond the environmental advantages inherent to GPAs, it is anticipated that ongoing advancements in alternative alkali materials will contribute to narrowing the cost differential between GPAs and natural aggregates in the future(L.-Y. Xu, Qian, et al., 2021).

5. Recent developments

The development of Phase Change Materials (PCMs) enriched geopolymer composites is an exciting field with significant advancements. These composites combine the unique properties of geopolymer materials with the thermal energy storage capabilities of PCMs.

This research aims to evaluate the potential of utilizing artificial geopolymer aggregates (GPAs) as a versatile and porous substrate for creating form-stable Phase Change Material (PCM) composites. GPA, a recently developed porous aggregate variant, is produced through the alkali-activation process using aluminosilicate-rich source materials (Qian et al., 2022; L.-Y. Xu et al., 2022; L.-Y. Xu, Huang, et al., 2021; L.-Y. Xu, Qian, et al., 2021). The GPA-PCM composite is prepared using a vacuum impregnation technique.

Drawing from previous studies, the addition of incinerated bottom ash to the GPA mixture has proven effective in increasing its porosity. This results in the creation of lightweight GPA with a reduced bulk density ranging from 1.52 to 1.62 and an increased water absorption capacity between 18.7% and 21.0%. Remarkably, despite its reduced density, this lightweight GPA maintains a robust compressive strength, ranging from 36.4 to 60.2 MPa.

The GPA-PCM composite is generated using a vacuum impregnation method. Building on earlier research, the inclusion of incinerated bottom ash into the GPA blend has shown to be a successful approach for enhancing its porosity. As a result, lightweight GPA with reduced bulk density (1.52–1.62) and improved water absorption capacity (18.7% to 21.0%) is achieved, while maintaining a substantial compressive strength (36.4 to 60.2 MPa).

Impregnating PCM into GPA leads to a partial reduction in the crushing strength of GPA-PCM, with reductions ranging from 4.13% to 25.46% when compared to GPA alone. The initial strength of GPA contributes to a more significant strength decline in GPA-PCM, primarily due to expansion stress during the phase transformation process. However, the GPA-PCM composites demonstrate remarkable thermal stability and exhibit significant melting enthalpy ranging from approximately 4.29 to 24.74 J/g. Additionally, the thermal conductivity of GPA-PCM ranges from 0.510 to 0.589 W/mK, surpassing that of GPA. Importantly, all GPA-PCM composites meet the established criteria for classification as insulation materials.

Geopolymers, known for their environmental benefits and versatility, have emerged as a sustainable alternative to conventional construction materials. Integrating biobased PCMs into geopolymer matrices presents an exciting avenue for enhancing the thermal performance and sustainability of these materials.

In a previous study, researchers conducted a comparative investigation involving three distinct form-stable composite Phase Change Materials (PCMs) designed for building applications. This research aimed to introduce the selected PCMs into pumice, a naturally occurring pozzolan known for its non-crystalline structure and porous nature. Pumice possesses exceptionally low density, substantial porosity, an extensive surface area, and limited chemical reactivity. These unique characteristics make pumice a promising candidate for efficiently absorbing PCM through surface tension and capillarity forces while maintaining a cost-effective preparation process (Karaipekli & Sarı, 2016).

Numerous researchers have dedicated their efforts to examining these bio-based PCMs that differ from paraffin-based ones. They have assessed these PCMs' appropriateness by evaluating their thermophysical properties, heat storage capacity, and parameters like phase-change enthalpy, specific heat capacity, and melting temperature. Despite these research efforts, it's essential to note that the existing body of literature provides only limited thermal data on these bio-based PCMs. Additionally, there are currently no established norms or standards for characterizing bio-based PCMs (Baetens et al., 2010).

The PCMs under scrutiny in this research investigation include a eutectic blend of capric acid and palmitic acid, dodecanol, and heptadecane. The study entails a comprehensive characterization of these composite materials, with a specific focus on evaluating their thermal properties, chemical stability, thermal stability, thermal cycling stability, and conducting microscopic examinations both before and after the impregnation process. The vacuum impregnation technique is employed for infusing the PCMs into the materials.

The study findings indicate that the Phase Change Material (PCM) exhibits no significant chemical reactivity with the carrier material, although some interactions between the PCM and the carrier were observed. Morphological analysis is conducted using scanning electron microscope (SEM) images. To assess the thermal stability of the PCM composite, thermogravimetric analysis is performed. Furthermore, the composite PCM undergoes 3000 thermal cycles involving phase transitions from solid to liquid and vice versa. The results from these cycling experiments demonstrate that the thermal performance of the composite PCM remains consistent throughout the entire spectrum of cycles examined.

Based on differential scanning calorimetry (DSC) tests, it is determined that the composite Phase Change Materials (PCM) are well-suited for applications within the temperature range of 21–23 °C. The research findings indicate that the pumice-heptadecane composite Phase Change Material (PCM) exhibits relatively superior thermal performance [46c].

Prior research has extensively investigated and documented the feasibility of utilizing bio-based fatty acids as thermal energy storage materials. These bio-based fatty acids are sourced from animal and plant oils, setting them apart from paraffins, which originate from finite, non-renewable fossil fuel reservoirs (Cellat et al., 2015).

Bio-based fatty acids, specifically sourced from animal and plant oils and distinct from paraffins extracted from non-renewable fossil fuel deposits, are explored. The research encompasses an investigation into organic compounds such as palmitic acid (PA), lauric acid (LA), myristic acid (MA), and capric acid.

A total of twelve binary mixtures are meticulously formulated, considering the desired indoor temperature range of 22–27 °C. These mixtures undergo thorough systematic evaluation of their thermal properties, with a particular emphasis on the CA-LA and CA-MA combinations. These combinations are singled out for potential integration into concrete to augment its thermal inertia. The selection criteria for these combinations are based on latent heat and phase transition temperatures obtained from measurements conducted using differential scanning calorimetry (DSC).

The analysis considers PCM concentrations of 1% and 2% by weight. Additionally, the incorporation of these PCMs into concrete leads to a substantial reduction in the concrete's hardening time.

This comprehensive review delves into the existing and prospective applications of biobased Phase Change Material (PCM)-enriched geopolymer matrices in the realms of building materials and energy-efficient construction.

Recent developments in Bio-Based PCM with geopolymer for Environmental Sustainability reflect the growing interest in eco-friendly construction materials and their potential to enhance energy efficiency. Notable trends include researchers exploring new and diverse sources for bio-based PCMs, such as agricultural waste, algae-derived lipids, and other sustainable feedstocks. These alternative sources increase the availability of bio-based PCMs and align with the goal of reducing waste and promoting circular economy principles(Bai & Colombo, 2018; Boussaba et al., 2019; de Albuquerque Landi et al., 2020; Fang et al., 2023; Mehrizi et al., 2023).

Advancements in microencapsulation and shape stabilization technologies enable the efficient incorporation of bio-based PCMs into geopolymer matrices. The development of hybrid materials that combine bio-based PCM-enriched geopolymers with other sustainable additives, such as aerogels or nanomaterials, is gaining traction. These combinations leverage the strengths of multiple materials to achieve superior thermal properties and overall performance (Fang et al., 2023).

Simulation and modeling tools are employed to assess the energy-saving potential of buildings incorporating Bio-Based PCM with geopolymer. This trend aids in optimizing the design and placement of these materials to maximize energy efficiency (Berardi & Gallardo, 2019). There is a growing emphasis on life cycle assessments, evaluating the environmental impact of these materials throughout their entire lifecycle. This approach provides a holistic view of their sustainability, from raw material extraction to disposal or recycling (Kumar et al., 2023).

Furthermore, emerging and evolving techniques include additive manufacturing, immersion and impregnation methods, reactive emulsion templating, particle compaction methods, and combined approaches (X. Zhang et al., 2021).

PCMs have been recognized as a favorable choice for advanced building insulation since the mid-1970s. Their application in buildings is aimed at enhancing energy efficiency by leveraging the specific characteristics of the surrounding environmental conditions (Rathore et al., 2020). PCMs primarily enhance the thermal attributes of structural components within which they are incorporated. They become active at distinct temperature thresholds, capturing thermal energy, which reduces the need for indoor heating and cooling, thereby advancing energy efficiency. PCMs can be integrated into building components via various methods, including direct admixture, immersion in liquid PCM, or encapsulation within other materials in the form of micro and macro capsules (Vicente & Silva, 2014).

Research focuses on optimizing the use of PCMs to reduce energy consumption in buildings and enhance energy efficiency. Investigations examine the integration of PCMs into traditional building materials. For instance, PCM can be incorporated into concrete to improve its thermal energy storage capacity (Cabeza et al., 2007; Ling & Poon, 2013; Ryms & Klugmann-Radziemska, 2019). In this context, a study investigated clay geopolymer mortar integrated with PCM, revealing a significant reduction in heat transfer compared to alternative mortar materials(Wang et al., 2016). Proper orientation is crucial for achieving optimal thermal comfort in indoor spaces, aligning construction materials with specific climatic conditions. Selection of PCM properties depends on climatic conditions, impacting the material's ideal melting temperature (Lagou et al., 2019; Park et al., 2021).

In addition to optimizing the thermal performance of PCMs, the focus has shifted toward minimizing the environmental impact of these materials. Life cycle assessments reveal variations in the environmental metrics associated with PCM production and efficacy, influenced by differences in assessment scope and boundary conditions. Embodied energy plays a pivotal role in PCM environmental characteristics, typically included in LCA analyses (Carbonaro et al., 2015; De Gracia et al., 2010; Kylili & Fokaides, 2016; Zhuk, 2019) [25e].

This comprehensive review explores the latest developments in PCM-enriched geopolymer matrices, emphasizing their applications, properties, and environmental benefits. By encapsulating PCMs within geopolymer structures, these innovative composites enhance thermal energy storage, improve temperature regulation in buildings, and reduce energy consumption. Through a thorough synthesis of research findings, this review underscores the potential of PCM-enriched geopolymer matrices as a sustainable solution for addressing environmental challenges in the construction sector.

In a previous research investigation, the primary focus was on utilizing artificial geopolymer aggregates (GPAs) as a medium for housing Phase Change Materials (PCMs), specifically designed for energy storage applications. The physical, mechanical, and thermal properties of GPA-PCM composites were thoroughly evaluated, showing that these properties can be adjusted by manipulating raw material constituents, such as slag content, water-to-binder ratio, and the inclusion of incinerated bottom ash (IBA). Increasing the IBA content was found to enhance the porosity of GPAs, thus increasing their PCM containment capacity.

Through a vacuum suction process, the absorption capacity reached a maximum of 16 wt% for Phase Change Material (PCM) within the artificial geopolymer aggregate (GPA), resulting in a substantial melting enthalpy of 24.74 J/g. Additionally, the GPA-PCM composite exhibited outstanding mechanical strength, surpassing 53.2 MPa, and demonstrated notable thermal conductivity ranging between 0.510 to 0.589 W/mK. Analysis of time-temperature history curves for GPA underscored that PCM impregnation resulted in impressive thermal regulation capabilities, achieving temperature differentials of up to 10.5 °C (Fang et al., 2023).

In a previous investigation, the focus was on integrating an innovative Phase Change Material (PCM) comprised of fatty acids, enclosed within a polyurethane foam matrix, into a geopolymer mortar matrix. The research involved a comprehensive analysis of the structural and thermal attributes of the developed geopolymer mortar (GP) and the form-stable PCM composite (PU@PCM). The inquiry also delved into the impact of PU@PCM inclusion on the mechanical properties of the geopolymer mortar, determined through compressive testing. Thermal behavior was systematically explored through thermogravimetric analysis (TGA), differential scanning calorimetry (DSC), and thermal conductivity measurements using the laser flash analysis (LFA) technique.

The findings from this study revealed that the synthesized geopolymer mortar forms a continuous and robust three-dimensional network structure. Simultaneously, the PU@PCM composite exhibited an operational temperature range from 10 to 22 °C, ideal for energy-efficient building design. The PU@PCM composite demonstrated an impressive energy storage capacity of ΔHf = 164 J/g. Despite a reduction in compressive strength due to PU@PCM incorporation, the composites continue to meet mechanical requirements for concrete applications, with the PU@PCM-rich composite achieving a notable strength of 29.5 MPa.

Moreover, the evaluation of thermal performance highlighted the substantial benefits of PU@PCM integration, particularly in terms of increased heat capacity and only a slight reduction in thermal conductivity within the composites. Specifically, the PU@PCM-rich composite exhibited heat capacity and thermal conductivity values of 1.1 J/g.°C and 0.84 W/m.°C, respectively.

Cyclic differential scanning calorimetry (DSC) tests confirmed the sustained thermal stability of the composites, even after enduring 20 heating and cooling cycles. In summary, the geopolymer mortar enriched with the highest PU@PCM content demonstrates robust potential as a promising candidate for the development of sustainable and energy-efficient buildings. This material combines commendable thermal performance with mechanical strength, making it suitable for practical applications in the construction industry(Haily et al., 2023).

In a prior study, a thermal energy storing cementitious composite was developed. This composite included microencapsulated Phase Change Material (PCM) encased in a bio-based polymer shell, referred to as m-PCM. The study also assessed the biodegradability of the PCM encapsulation through Nuclear Magnetic Resonance (NMR), confirming the high biodegradability of the m-PCM shell under specific environmental conditions.

The thermophysical properties of the m-PCM were characterized using Differential Scanning Calorimetry (DSC) and Thermogravimetric analysis (TGA). DSC analysis revealed exothermic enthalpies of 84.7 J/g and 140.2 J/g, along with associated peak temperatures of -3.2 °C and -22.9 °C, respectively. Subsequently, the m-PCM was incorporated into cement-based mortar at varying proportions of 5%, 10%, and 15% by weight of the binder.

The findings demonstrate that, in comparison to other sets of microcapsules, LP-4 exhibits a favorable level of biodegradability, characterized by an average particle size of 6.6 µm. Furthermore, LP-4 boasts a notably higher core material active content, surpassing other samples by 42.6%. Analysis using Nuclear Magnetic Resonance (NMR) revealed that LP-4 capsules exhibit the most significant biodegradability when exposed to environmental conditions, showing a remarkable 56.39% reduction in peak intensity.

Furthermore, the thermal assessment of the LP-4 PCM microcapsules, as developed in this study, exhibited commendable thermal performance and can be effectively integrated into construction materials to enhance their thermal inertia. Differential Scanning Calorimetry (DSC) results indicated that the m-PCM released substantial heat energy, measuring at 84.76 J/g and 140.2 J/g, with peak temperatures of -3.2 °C and -22.9 °C, respectively.

The nanomodified thermal energy storage cementitious composite developed in this study possesses adequate mechanical strength for application as a construction material in low-temperature scenarios. Thermal cycling tests corroborate that the inclusion of m-PCM in the mortar substantially enhances their thermal inertia. However, it is important to note that due to the supercooling effect, P5 and CSP 5 demonstrated lower efficiency compared to P10 and P15. However, the introduction of highly thermally conductive Multi-Walled Carbon Nanotubes (MWCNTs) improved the thermal efficiency of the specimens (X. Jin et al., 2023).

In summary, the development of PCM-enriched geopolymer composites is an evolving field with ongoing research aimed at enhancing their thermal properties, reducing costs, and expanding their applications. These developments have the potential to revolutionize multiple industries by providing efficient and sustainable solutions for thermal energy storage and management.

6. Applications and Emerging Trends

Phase Change Materials (PCMs) enriched geopolymer composites are a fascinating and innovative area of research in materials science and construction engineering. Geopolymers are a type of environmentally friendly, cementitious material that can be used as an alternative to traditional concrete, and when combined with PCMs, they offer a range of applications and emerging trends.

The emergence of 3D printing has ushered in a paradigm shift in conventional construction practices, offering a cost-effective and expeditious means of fabricating intricate architectural structures. Nonetheless, there persist unresolved challenges concerning the efficacious incorporation of functional additives into 3D printing construction materials. A preceding research article has introduced a straightforward and environmentally conscientious approach designed to advance the cause of sustainable building construction while concurrently curbing energy consumption.

This approach involves the amalgamation of Macroencapsulated Phase Change Materials (MEPCM) into a 3D printable geopolymer paste (GPP), which is synthesized from fly ashes. The research was executed meticulously, encompassing a comprehensive evaluation of the immediate and long-term properties of geopolymer pastes with varying proportions of MEPCM. Additionally, the study involved an in-depth analysis of the thermal properties of these formulations and an assessment of their thermal performance, accomplished by the fabrication of miniature structures using 3D printing technology. This assessment compared structures produced without MEPCM to those containing 20% MEPCM.

Remarkably, MEPCM displayed a dual functionality, serving as a pivotal component for the management of thermal energy within the structures and as a modifier of the viscosity of the 3D printable geopolymer paste. In summary, this study introduces an innovative trajectory towards sustainable construction, accentuating the paramount importance of enhancing energy efficiency and curtailing wasteful practices within the construction sector(Rahemipoor et al., 2023).

Previous research article outlines an experimental investigation involving the characterization of a wall assembly constructed from geopolymer concrete and phase change materials (PCMs) in the context of the climate of southern Italy. Data collected during the period from May to July 2021 were analyzed, focusing on surface temperatures and heat fluxes. This analysis introduced several novel indices, including the thermal stress reduction amplitude, the percentage of time within the melting range, and extreme surface stresses.

The results of the study demonstrate that the incorporation of PCMs effectively mitigates thermal stress and safeguards the integrity of the geopolymer blocks. Notably, during periods of peak solar exposure, the indoor surface temperature experiences a reduction of up to 3°C. This reduction contributes significantly to alleviating localized thermal discomfort. On a broader scale, the heat flux measured within the geopolymer layer located behind the PCM exhibits attenuation, resulting in a more consistent trend. This reduction in heat flux translates to decreased heat ingress through the opaque building envelope, ultimately leading to a reduction in energy demand (De Masi et al., 2023).

This study investigates the energy and environmental performance of Phase Change Material (PCM) coatings as a retrofit solution for walls in existing buildings. A validated model was utilized to calculate the total heat flux over the course of one year, considering three distinct geographical locations and four different orientations of the building. Additionally, the study establishes the energy payback period for the proposed PCM solutions, which is defined as the ratio between the embodied energy of the materials and the reduction in heat flux through the building element.

The findings indicate that the placement of the PCM layer has a significant impact on the energy performance of the building element. Notably, positioning the PCM layer on the external side of the wall is identified as the optimal solution, irrespective of the building's orientation. Furthermore, the study discerns variations in the performance of PCM coatings for different orientations of the building.

The effectiveness of the PCM coatings is observed to be more pronounced for structures with eastern and western orientations in warm-dominant climates (e.g., Athens), and for those with northern orientations in cold-dominant climates (e.g., Copenhagen). The research also reveals specific instances where PCM coatings yield substantial energy savings, such as 4.8 kWh/m2 per annum with an energy payback period of 1.5 years for western orientation in Athens, and 29.84 kWh/m2 per annum with an energy payback period of 0.8 years for northern orientation in Copenhagen.

The energy payback period for PCM coatings is shown to vary significantly, ranging from 0.8 to 30 years, depending on the installation location and the building's configuration. This underscores that there are situations where the installation of PCM coatings may not be environmentally and economically feasible (Georgiou et al., 2023).

7.Persistent Challenges:

Persistent challenges in Bio-Based PCM-with geopolymer for environmental Sustainability are essential considerations for researchers and industry professionals aiming to maximize the potential of these materials.

7.1 Phase Transition Temperatures: Selecting PCMs with appropriate phase transition temperatures that align with the desired thermal performance of the geopolymer composite can be complex. The PCM's transition temperature should ideally match the building's temperature fluctuations, which vary by climate and location (Rehman et al., 2022; Sun et al., 2022).

7.2 PCM Dispersion: Achieving uniform dispersion of PCMs within the geopolymer matrix without agglomeration or settling is crucial for maintaining consistent thermal properties. Further, achieving compatibility between bio-based PCMs and geopolymer matrices can be challenging. Ensuring that these components interact seamlessly without causing separation, degradation, or phase separation is crucial for the materials' effectiveness and long-term stability (Marani & Nehdi, 2019).

7.3 PCM Compatibility and Leakage: Ensuring that the PCM is chemically compatible with the geopolymer binder and does not compromise the mechanical strength or durability of the composite (Messenger et al., 2023). Preventing PCM leakage, especially in high-temperature environments, is essential to avoid structural and environmental issues. The quality assurance of composite matrices necessitates addressing challenging research areas, including the complete prevention of Phase Change Material (PCM) leakage into the matrix, ensuring robust long-term cyclic stability, and minimizing any adverse impact on compressive strength(R. Sharma et al., 2022).

7.4 Production Costs and Long-Term Performance: PCMs can be relatively expensive, so cost-effectiveness must be considered when incorporating them into geopolymer composites for widespread use. Assessing the long-term durability and stability of PCM-geopolymer composites, including their ability to withstand repeated phase transitions and cyclic thermal stresses(Łach et al., 2021).

7.5 Impact on Workability; Scale-Up Challenges; Environmental Impact: Evaluating how the addition of PCMs affects the workability and setting characteristics of the geopolymer mix, which may require adjustments to the manufacturing process. Moving from laboratory-scale experiments to large-scale production presents logistical and economic challenges that need to be addressed. Conducting a comprehensive Life Cycle Assessment (LCA) to determine the overall environmental impact of PCM-geopolymer composites and ensure that they align with sustainability goals. Further researchers must assess factors such as material aging, resistance to moisture, thermal cycling, and structural integrity over time and compatibility (Regin et al., 2008; Reyez-Araiza et al., 2021).

Overcoming these challenges is essential for the successful integration of PCMs into geopolymer composites, ultimately contributing to enhanced thermal performance and energy efficiency in buildings and construction applications.

8.Future Prospects:

Predictions for the future of biobased PCM-enriched geopolymers include their potential use as thermoregulatory materials (Korniejenko et al., 2022). Bio-based PCMs have large latent heat, low vapor pressure, and good chemical stability, making them promising candidates for various applications. Geopolymers and their composites, including those enriched with biobased PCMs, have advantages such as low-temperature preparation, low cost, and heat resistance. These materials can be used in conventional construction, metallurgy, and aerospace industries. The development of bio-based polymers from renewable resources, including those used in geopolymers, is gaining attention due to environmental concerns and the finite nature of petroleum resources (Jeong et al., 2014; Jia et al., 2020). The combination of biobased PCMs and geopolymers offers the potential for enhanced thermal properties and durability, making them suitable for future applications in fields such as civil engineering and energy storage.

Future directions in Bio-Based PCM-enriched geopolymer for environmental sustainability involve innovative strategies and research priorities to further advance these materials' contributions to greener and more energy-efficient construction practices. Continued exploration of sustainable and diverse sources for bio-based PCMs is crucial. Research should focus on identifying novel feedstocks and extraction methods to ensure a stable and environmentally friendly supply of bio-based PCMs (Nazari Sam et al., 2020). Enhancing microencapsulation and shape stabilisation methods to improve the stability, dispersion, and thermal performance of bio-based PCMs within geopolymer matrices. Innovations in shape stabilisation technologies can lead to materials with superior thermal properties(Marani & Nehdi, 2019). Developing Bio-Based PCM Enriched Geopolymer materials with tailored properties for specific climate zones and building applications. This customization ensures optimal performance and energy savings in diverse environmental conditions (Boussaba et al., 2019). Conducting comprehensive life cycle assessments to evaluate the environmental impact of these materials throughout their entire lifecycle. This approach provides a holistic view of their sustainability, guiding further improvements. Continued development and refinement of energy simulation and modelling tools to accurately predict the energy-saving potential of buildings incorporating these materials. This aids architects and engineers in optimizing designs for maximum efficiency(Kumar et al., 2023). Investigating opportunities for recycling and repurposing of Bio-Based PCM Enriched Geopolymer materials at the end of their lifecycle to minimize waste and promote circular economy principles (Ong et al., 2023).

The amalgamation of PCM performance data with Life Cycle Assessment (LCA) indicators also creates opportunities for future research endeavors aimed at extracting and establishing indicators linked to the overall energy performance of materials over their entire lifecycle.

The scope of this study is amenable to future expansion, with the potential inclusion of alternative PCM variants and consideration for a broader spectrum of climatic conditions and weather patterns (Georgiou et al., 2023).

Lastly, delving into the potential utilization of alternative polymers for the encapsulation of the investigated energy storage material holds promise for fostering greater innovation and sustainability within the realm of construction materials. These research domains have the capacity to fine-tune the developed geopolymer mortars and chart the course towards the emergence of ecologically innovative building materials, which are of paramount importance in the pursuit of a sustainable future and in mitigating the adverse consequences of climate change (Walubita et al., 2022). In summary the future direction of Phase Change Materials (PCM)-based geopolymer composites holds significant potential for advancing sustainable construction and energy-efficient building practices. Several key directions and trends are likely to shape this field are tailored PCM, improved PCM dispersion, multifunctional composites, nanomaterials, large scale applications, life cycle assessment and smart building integration. As these directions unfold, PCM-based geopolymer composites are expected to play an increasingly important role in enhancing the energy efficiency, thermal comfort, and sustainability of buildings, contributing to global efforts to mitigate climate change (Georgiou et al., 2023; Walubita et al., 2022).

9.Conclusion:

The prime objective of this research was to conduct a comprehensive analysis of the Developments, Trends, Challenges and Future direction associated with bio-based Phase Change Materials (PCMs) in geopolymer matrices. However, the continued research and innovation in this field hold the potential to revolutionize the construction industry, making buildings more energy-efficient, environmentally friendly, and sustainable. These materials are poised to play a vital role in shaping the future of green construction practices. These recent trends collectively highlight the growing momentum and potential of Bio-Based PCM Enriched Geopolymer materials in advancing environmental sustainability in the construction industry.

However, additional research endeavours are essential to explore the processing of these PCMs and to comprehensively assess their thermophysical and mechanical characteristics, both at the micro and macro scales. This evaluation is critical in determining the viability of substituting conventional petroleum-based PCMs with environmentally sustainable bio-based alternatives. Overcoming obstacles is crucial for unlocking the full potential of Bio-Based PCM in Geopolymer materials and advancing environmental sustainability in the construction sector. The future direction of Bio PCM-Geopolymer is characterized by a commitment to sustainability, innovation, and practical application. As these materials continue to evolve, they hold great potential to transform the construction industry and contribute significantly to energy-efficient, environmentally responsible building practices. By addressing these future directions, the construction industry can harness the full potential of Bio-Based PCM in Geopolymer materials to significantly reduce energy consumption, lower carbon emissions, and promote more sustainable and environmentally responsible building practices.

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