

Enhanced Thermal Energy Storage in Buildings: Impregnation, Leakage, and Environmental Performance of Organic and Inorganic PCM Composites

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RESEARCH ARTICLE

Enhanced Thermal Energy Storage in Buildings: Impregnation, Leakage, and Environmental Performance of Organic and Inorganic PCM Composites

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ABSTRACT

This study experimentally investigates the impregnation and leakage performance of various organic (tobacco, sawdust, bay leaf, black cumin) and inorganic (vermiculite, perlite, bentonite, sepiolite) carrier materials used for phase change material (PCM) integration in building applications. The commercial paraffin-based PCM RT-31 was used as the thermal storage medium. Impregnation and leakage tests were conducted to evaluate the PCM absorption capacity, form stability, and energy storage potential of each carrier. The results revealed that perlite (C = 80%) and bay leaf (C = 78%) exhibited the highest impregnation capacities due to their porous and fibrous structures; however, they also demonstrated significant leakage tendencies ($\approx 19\text{--}20\%$). Conversely, bentonite and black cumin composites showed excellent form stability, with leakage ratios as low as 3.6% and 4.2%, respectively. These findings indicate that while highly porous materials offer superior energy storage potential, layered structures provide improved PCM retention and leakage resistance. Additionally, life cycle assessment (LCA) analysis using the ReCiPe 2016 method identified wood-based PCM composites as the most environmentally sustainable option. The study contributes to the development of eco-friendly, thermally efficient building materials by optimizing the balance between storage capacity and form stability in PCM composites.

Keywords: Phase change material (PCM), Porous carriers, Leakage resistance, Thermal energy storage, Sustainable building materials, Life cycle assessment (LCA)

1. Introduction

Global warming has become a serious threat to humanity and a major global concern. Among the main triggers of this climatic crisis are various harmful emissions such as CO₂. In this context, the construction industry, which plays a decisive role in global energy consumption and greenhouse gas emissions, is a key sector that directly affects climate change [1]. Similarly, studies in the literature report that buildings account for approximately 36% of the world's annual energy consumption, of which nearly 53% is

attributed to heating and cooling operations within HVAC systems [2, 3]. The projected dramatic increase in cooling and heating energy demand by 2050 indicates that the current energy crisis will further intensify [4]. Research has shown that the effective control of indoor temperature can lead to significant reductions in energy consumption associated with heating and cooling loads [5]. Moreover, the development of eco-friendly building materials supported by new-generation solutions is considered one of the main strategies contributing to reduced energy use [6]. Since buildings are among the primary sources of

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energy consumption, climate change, and greenhouse gas emissions, mitigating global warming requires not only the reduction but also the complete elimination of CO₂ emissions arising from human activities such as fossil fuel use, cement production, and deforestation [7]. Within this framework, one of the most promising approaches to improving building energy efficiency is thermal energy storage (TES) technology. TES systems are gaining increasing importance as they help balance energy demand while maintaining indoor comfort sustainably [8]. TES technologies, particularly due to their potential for improving energy efficiency in buildings, have attracted considerable attention in recent years [8]. In simple terms, TES refers to the process of storing heat for later use. The stored energy can be utilized for both heating and cooling applications [9]. One form of TES, known as latent heat storage, is achieved using Phase Change Materials (PCMs), which include organic, inorganic, and eutectic (low-melting) mixtures. PCMs absorb and release heat through phase transitions—typically by taking up energy from a hot medium during the charging process and releasing it to a cooler medium during the discharging process [10, 11]. A major advantage of PCMs is their contribution to thermal comfort and energy efficiency. Consequently, PCMs have been increasingly integrated into building materials, structural components, façades, roofs, and floors to reduce energy consumption. The number of studies focusing on PCM applications in building materials and components has significantly increased in the recent literature. The integration of PCMs into building components has been shown to reduce heating and cooling energy demands while stabilizing interior surface temperature fluctuations. For instance, a study conducted in Iran reported that integrating PCM layers into the walls of a three-story residential building reduced cooling energy consumption by 5.4% and heating energy consumption by 18.9% [12]. Similarly, research under Saudi Arabian climatic conditions demonstrated that embedding PCM within square-cavity bricks significantly decreased heat flux, with the performance varying depending on PCM type and cavity configuration [13]. Experimental studies using PCM-infused bricks have revealed that interior surface temperatures during daytime were 4–9.5 °C lower compared to conventional bricks [14]. Moreover, when PCM was mixed with cement and silica fume for plaster applications, studies reported reduced indoor surface temperature fluctuations and increased heat storage capacity under different climatic conditions [15]. However, one of the major challenges in integrating PCMs into building elements is the leakage problem occurring during the phase transition, which significantly reduces ther-

mal energy storage efficiency. Therefore, developing supporting matrices that provide both structural stability and high heat storage capacity while preventing leakage is crucial [16, 17]. The use of porous carriers is a common approach for PCM stabilization, as these structures absorb the PCM and act as physical barriers, thereby minimizing leakage risk [18]. As a result, various composite configurations have been proposed in the literature to overcome this limitation. Form-stable phase change materials, also referred to as shape-stable phase change materials, are composite materials consisting of at least one PCM contained within a solid matrix. When the PCM melts, the liquid phase remains trapped within the supporting structure, thereby preventing leakage. Consequently, form-stable PCMs can be used without additional encapsulation and maintain their structural integrity regardless of the phase state of the PCM [19]. To achieve a form-stable composite, the supporting material must possess high absorption capacity, suitable porosity, and material compatibility [17]. In this context, factors such as absorption capacity, durability, chemical stability, toxicity, and cost are key criteria in carrier selection. A wide range of porous materials has been investigated to develop form-stable PCM composites. Among them, vermiculite [20, 21], attapulgite, diatomite [22–24], expanded clay [25], expanded graphite [26, 27], expanded perlite [28, 29], and ceramic foams [30], are particularly notable. Recently, the use of biomass-based carriers has increased, and porous biomaterials such as corn cob [31], rice husk ash [16], coconut shell–corn cob mixture [32] and luffa fiber [33] have emerged as promising alternatives due to their environmental sustainability and economic feasibility. The main objective of this study is to experimentally compare the PCM absorption and leakage performance of various organic (tobacco, sawdust, bay leaf, black cumin) and inorganic (vermiculite, perlite, bentonite, sepiolite) carrier materials (Fig. 1). Within this scope, the study aims to identify natural or mineral-based carriers that can prevent leakage during the melting–freezing cycles of PCMs while improving mechanical strength, thermal conductivity, and heat storage capacity. Thus, the study seeks to contribute scientifically and practically to the development of sustainable building materials that enhance energy efficiency.

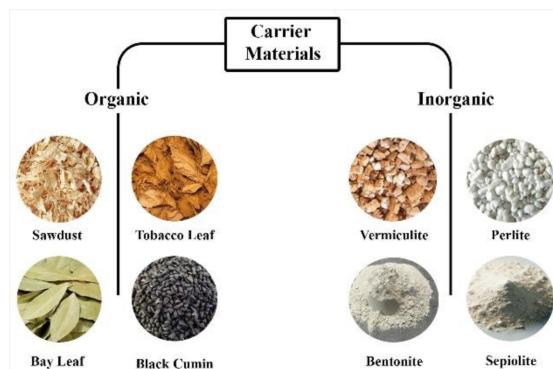
2. Experimental

2.1. Materials

In the experiments, a commercial phase change material (PCM) named RT-31 produced by Rubitherm Technologies GmbH was used. Rubitherm RT-31 is

Table 1. Thermo-physical properties of the phase change material (RT-31).

	Melting Range (°C)	Freezing Range (°C)	Heat Storage Capacity $\pm$ % 7,5(kJ/kg)	Specific Heat Capacity (kJ/kg.K)	Solid Density (kg/l)	Liquid Density (kg/l)	Thermal Conductivity (katı/sıvı) [W/(m.K)]	Volume Expansion (%)	Flash Point (°C)	Maximum Operating Temperature (°C)
RT-31	29-34 Main peak (31 °C)	34-29 Main peak (31 °C)	165	2	0,83	0,76	0,2	12,5	157	50

**Fig. 1.** Carrier materials used in the study.

a pure paraffin-based PCM that stores and releases a large amount of thermal energy at nearly constant temperature during the solid–liquid (melting and freezing) phase transitions [34]. According to the technical data sheet provided by the manufacturer [34], the thermo-physical properties of the paraffin are listed in Table 1.

In selecting carrier materials, special attention was given to their porous structure, which enables high PCM retention capacity. Accordingly, natural organic carriers such as sawdust, dried tobacco leaves, dried bay leaves, and black cumin seeds were selected, while mineral-based inorganic carriers included expanded perlite, vermiculite, sepiolite, and bentonite.

Wood is a natural, anisotropic material that exhibits direction-dependent properties due to its fibrous structure. The microchannels aligned along the fibers allow effective directional transport of heat and mass. This fibrous–porous architecture provides advantages for both thermal and fluid transfer, making wood an excellent material for applications requiring oriented heat conduction. Furthermore, the porous matrix between fibers facilitates the impregnation of PCMs, allowing wood to serve as a cost-effective and stable carrier material [35–37]. Tobacco leaves possess a fibrous and veined porous structure, offering a large surface area and strong absorption capacity [38–40]. However, no studies in the literature have yet reported their integration with PCMs. Bay leaves

are also rich in fibrous content. Their fibrous structure contributes to natural absorption behavior and mechanical stability [41, 42]. Black cumin (*Nigella sativa*) seeds and shells, due to their fibrous and porous nature, have been widely studied as biosorbents for removing heavy metals and dyes, and in biomedical fields for fabricating porous fibrous scaffolds used in bone regeneration [43–45]. Nevertheless, no studies have yet explored the use of bay leaves or black cumin as carrier matrices for PCM impregnation. Among the inorganic materials, vermiculite and perlite—both of volcanic origin—are highly absorbent due to their porous structure. When expanded by heating, their volume increases several times, forming a more porous structure. Owing to these characteristics, both materials are commonly used in the development of composite phase change materials [46–49]. Sepiolite and bentonite, on the other hand, are natural clay minerals known for their high surface area and adsorption capacity derived from their porous structures. Sepiolite’s fibrous morphology and strong adsorptive properties, as well as bentonite’s high swelling capacity, make them particularly suitable for sealing and drilling applications [50, 51]. The remarkable absorbency of bentonite is attributed to its layered structure, where interlayer spaces allow water and ions to penetrate, resulting in significant swelling and high absorption capacity [52]. Numerous studies have demonstrated that these minerals are frequently utilized in the fabrication of composite PCMs due to their excellent surface adsorption characteristics [53–56].

2.2. Experimental methods

In this study, impregnation experiments were carried out using different organic and inorganic carrier materials combined with a phase change material (PCM). Subsequently, leakage tests were performed on the obtained composite samples. The experimental data enabled a comparative evaluation of the PCM retention capacities and leakage resistance performance of the carrier materials.



Fig. 2. (a) heated magnetic stirrer; (b); muffle furnace.

2.2.1. Impregnation experiment

The impregnation process was conducted in two stages. In the first stage, each carrier material was sequentially immersed into the liquid PCM using a heated magnetic stirrer to ensure uniform mixing and thermal equilibrium. In the second stage, the impregnated samples were placed in a high-temperature-resistant muffle furnace equipped with internal thermal insulation and kept at 90 °C for 90–120 minutes to complete the impregnation process (Fig. 2).

The experimental conditions for the impregnation process are listed in Table 2.

After the impregnation process was completed, excess PCM was drained, and the remaining composite mixtures were poured into cylindrical molds and left to stabilize at room temperature. The demolded samples were then prepared for leakage testing. The impregnation capacity (C) was calculated using the equation proposed by [57], which indicates the proportion of the composite that effectively participates in thermal energy storage through PCM content:

Impregnation Capacity (C%) =

$$\frac{M_0 - M_{\text{carrier}}}{M_0} \times 100 \quad (1)$$

M_{carrier} : The mass of the carrier in the composite

M_0 : The composite formed at the end of the impregnation experiment

Additionally, the amount of PCM absorbed by the carrier after the impregnation process was quantified by the Mass Percentage Gain (MPG), as defined by [58],

Mass Percentage Gain (%) =

$$\frac{M_0 - M_{\text{carrier}}}{M_{\text{carrier}}} \times 100 \quad (2)$$

M_{carrier} : The mass of the carrier in the composite

M_0 : The composite formed at the end of the impregnation experiment

This value represents the percentage of PCM absorbed relative to the initial mass of the carrier material.

2.2.2. SEM analysis

Scanning Electron Microscopy (SEM) analyses were carried out on representative samples selected to investigate the morphological and microstructural properties of the prepared PCM composites. The porous structure of the matrix materials was assessed using SEM images, and the penetration of the PCM into the matrix structure was examined qualitatively.

2.2.3. DSC analysis

A TA Instruments DSC Q2000 differential scanning calorimeter (DSC) was used to evaluate the phase transition behavior and thermal storage properties of selected PCM composites. Tobacco leaf, pure paraffin, and perlite samples were evaluated separately in the analyses. Measurements were carried out under inert atmosphere conditions, using nitrogen gas at a flow rate of 50 mL/min throughout the system. Samples were heated in a controlled manner from 15 °C to 60 °C, held at the maximum temperature for 1 minute, and then cooled back to 15 °C. Thus, endothermic and exothermic transitions occurring during both heating and cooling cycles were investigated.

2.2.4. Leakage test

After the impregnation experiment, the demolded composite samples were prepared for the leakage test. To observe the extent of PCM leakage, the samples were placed on papers of identical size and then kept in a drying oven at 50 °C for 120 minutes. The leakage behavior of each sample was recorded photographically at 15-minute intervals throughout the test duration. The experimental conditions for the leakage test are presented in Table 3.

The leakage ratio (L%) was calculated to assess the form stability of each composite, representing the percentage of mass loss relative to the initial composite mass [59]:

Table 2. Experimental conditions for impregnation of organic and inorganic carrier materials.

Carrier	Material	Photo	Mass of Carrier (g)	Furnace Time (min)	Furnace Temperature (°C)
Inorganic	Vermiculite		1,03 gr	90 dk	90 °C
Materials	Perlite(expanded)		0,7 gr	120 dk	90 °C
	Bentonite		5,67 gr	120 dk	90 °C
	Sepiolite		2,50 gr	120 dk	90 °C
Organic	Tobacco Leaf (powdered)		0,65 gr	120 dk	90 °C
Materials	Black Cumin		5,28 gr	120 dk	90 °C
	Sawdust		1,01 gr	90 dk	90 °C
	Bay Leaf (powdered)		0,74 gr	120 dk	90 °C

Leakage Ratio (%) =

$$\frac{M_0 - M_1}{M_0} \times 100 \quad (3)$$

M_0 : The initial composite mass

M_1 : Composite mass at the end of the leakage test

This equation is widely used to quantitatively determine the amount of PCM that leaks from the carrier matrix during thermal exposure. In the impregnation of phase change materials (PCMs) into porous carriers, the loading ratio is a critical parameter for evaluating material performance. It indicates the percentage of PCM within the composite by mass and directly affects both energy storage capacity and structural stability. The PCM loading ratio was determined using the following equation [60]:

PCM Loading Ratio (%) =

$$\frac{M_1 - M_{carrier}}{M_1} \times 100 \quad (4)$$

M_1 : Composite mass at the end of the leakage test

$M_{carrier}$: The mass of the carrier in the composite

3. Findings

In this section, the data obtained from the impregnation and leakage experiments are presented, and the performance of different organic and inorganic carrier materials is compared. The findings are evaluated in terms of the carriers' PCM absorption capacity, leakage resistance, and thermal energy storage potential.

The obtained results are detailed through tables and graphical representations, providing a comprehensive assessment of the relationship between carrier structure, PCM retention efficiency, and form stability.

3.1. PCM impregnation test results

In this study, both organic and inorganic carrier materials exhibited different levels of absorption performance during the impregnation experiments. The results of the impregnation tests for organic and inorganic carriers are presented in Table 4.

The impregnation performance of various organic and inorganic carrier-PCM composites was evalu-

Table 3. Experimental conditions for the leakage test of organic and inorganic PCM composites.

Carrier	Material	Photo	Carrier Mass (g)	Composite Mass (Carrier + PCM)(g)	Duration (min)	Temperature (°C)
Inorganic	Vermiculite		1,03 gr	2,47 gr	120 dk	50 °C
Material	Perlite(expanded)		0,7 gr	3,60 gr	120 dk	50 °C
	Bentonite		4,22 gr	9,14 gr	120 dk	50 °C
	Sepiolite		1,98 gr	4,36 gr	120 dk	50 °C
Organic	Tobacco Leaf (powdered)		0,65 gr	1,80 gr	120 dk	50 °C
Material	Black Cumin		5,28 gr	7,83 gr	120 dk	50 °C
	Sawdust		1,01 gr	1,81 gr	120 dk	50 °C
	Bay Leaf (powdered)		0,70 gr	3,25 gr	120 dk	50 °C

Table 4. Impregnation test results of inorganic and organic carrier materials.

Carrier	Materials	Composite Mass (Carrier + PCM) (g)	Absorbed PCM Mass (g)	Impregnation Capacity (C)(%)	Mass Percentage Gain (MPG)(%)
Inorganic Materials	Vermiculite	2,47 gr	1,44 gr	58	139
	Perlite(expanded)	3,60 gr	2,90 gr	80	414
	Bentonite	9,14 gr	6,58 gr	53	116
	Sepiolite	4,36 gr	3,01 gr	54	120
Organic Materials	Tobacco (powdered)	1,80 gr	1,15 gr	63	176
	Black Cumin	7,77 gr	2,49 gr	32	48
	Sawdust	1,80 gr	0,79 gr	44	79
	Bay Leaf (powdered)	3,24 gr	2,50 gr	78	364

ated using Impregnation Capacity (C%) and Mass Percentage Gain (MPG%) parameters. According to the results, expanded perlite (C = 80%; MPG = 414%) and bay leaf (C = 78%; MPG = 364%) exhibited the highest impregnation capacities, which can be attributed to their highly porous and fibrous structures that promote PCM absorption. In contrast, bentonite (C = 53%) and sepiolite (C = 54%), both clay-based inorganic carriers, demonstrated moder-

ate impregnation performance, likely due to their layered internal structure that partially restricts PCM penetration. Among the organic carriers, black cumin (C = 32%) and sawdust (C = 44%) showed limited PCM absorption capacity, indicating that their pore structure and surface chemistry were less favorable for PCM retention. A generally positive correlation was observed between impregnation capacity and mass percentage gain across all samples. The supe-

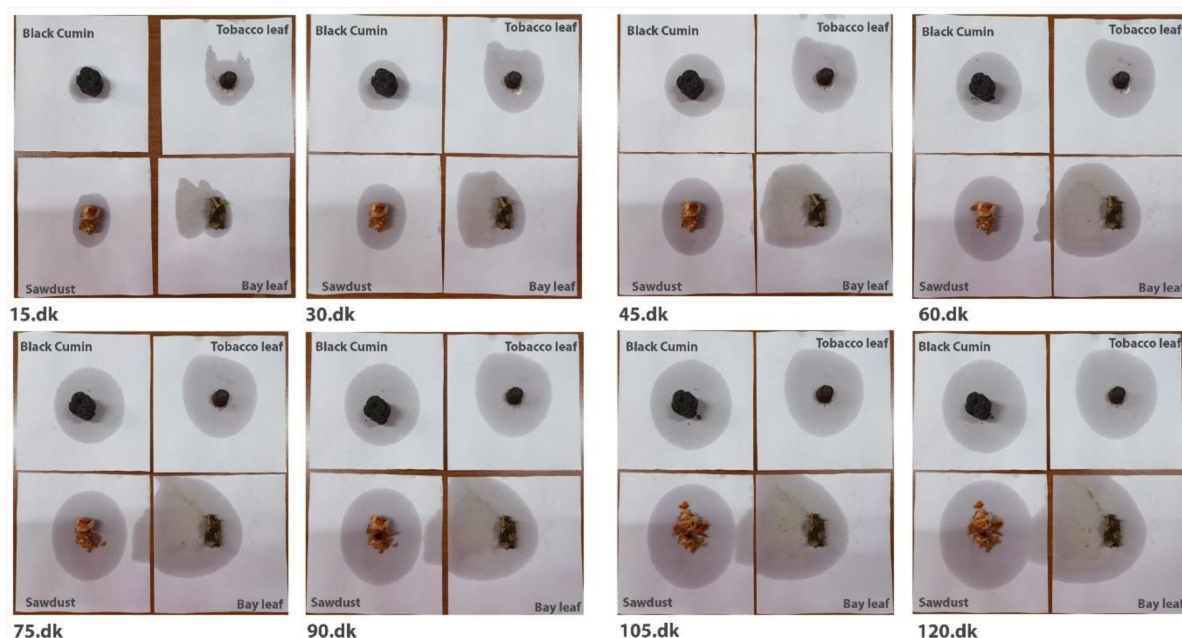


Fig. 3. Photographic sequence of the leakage test for organic PCM composites.

rior performance of perlite and bay leaf indicates that PCM effectively penetrated the carrier matrix, forming well-impregnated composites with potentially enhanced energy storage efficiency.

3.2. PCM leakage test results

The form stability of the composite samples was evaluated by visually monitoring the leakage of PCM during the heating process. For this purpose, each sample was placed on a white surface and photographed at 15-minute intervals for up to 120 minutes. The visual records provided qualitative information about both the PCM retention capacity of each carrier and its stability during phase transition under thermal exposure (see Fig. 3 and Fig. 4).

As observed in the images, most samples maintained their structural integrity during the initial 15–30 minutes. However, between 45 and 120 minutes, the sawdust and vermiculite composites lost their form stability and disintegrated. In contrast, bentonite composites retained their shape throughout the test, showing only minimal traces of leakage around the edges. This behavior can be attributed to the layered structure of bentonite, which effectively traps PCM within its interlayer spaces. The sepiolite and perlite composites exhibited wide and well-defined leakage rings, consistent with their high impregnation capacities. The high PCM loading in these materials also increased their tendency to leak. Similarly, bay leaf and sawdust samples showed

extensive PCM spreading, indicating that bay leaf, despite its high loading ratio, possessed weak form stability. On the other hand, black cumin and tobacco leaf composites formed smaller leakage halos; notably, the black cumin samples showed limited surface staining, suggesting that their pore structure allowed for balanced PCM retention. The visual leakage results correlated well with the quantitatively determined leakage ratio (L%) values. The experimental results for the leakage tests of organic and inorganic composites are summarized in Table 5.

The form stability of the composites was quantitatively evaluated using the Leakage ratio (L%) and the PCM loading ratio (%) values obtained after the leakage test. According to the results, bentonite ($L = 3.6\%$) and black cumin ($L = 4.2\%$) exhibited the lowest leakage ratios, indicating superior structural stability. The excellent retention capacity of bentonite can be explained by its porous and layered microstructure, which effectively confines PCM molecules within interlayer gaps. In contrast, perlite ($L = 19.4\%$), sepiolite ($L = 20.1\%$), and bay leaf ($L = 20\%$) showed the highest leakage ratios. Although these materials demonstrated high PCM loading ratios (75% for perlite and 71% for bay leaf) their open-pore structure facilitated PCM migration and surface spreading during heating. Therefore, while a higher PCM loading ratio corresponds to greater energy storage capacity, the same structural characteristics may simultaneously promote higher leakage tendency. Additionally, black

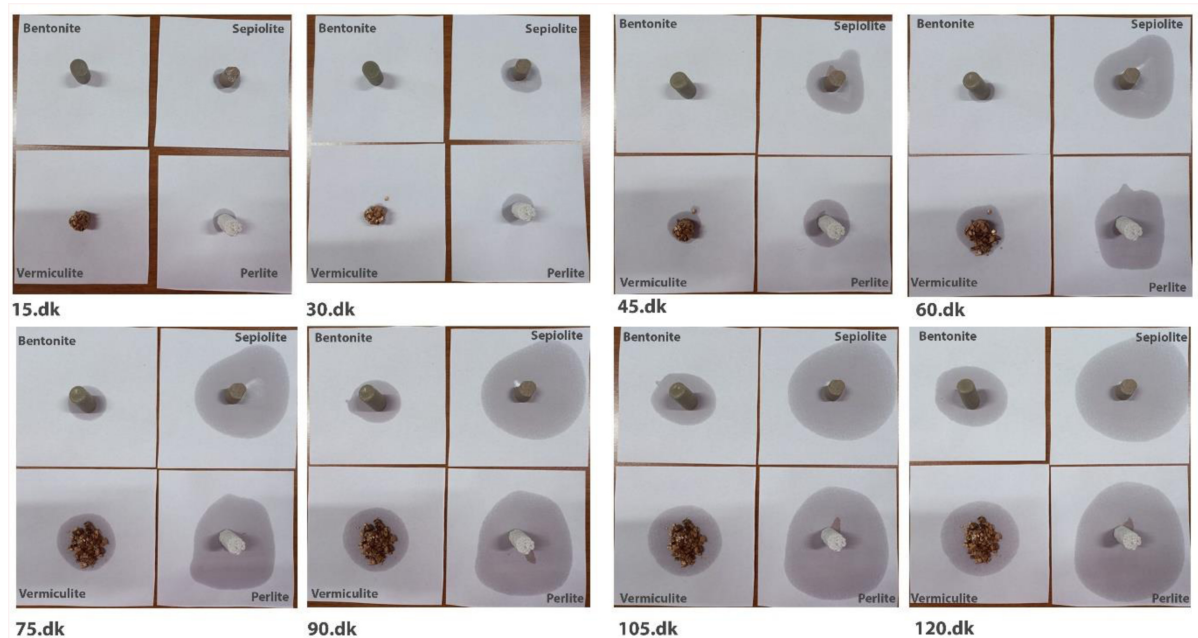


Fig. 4. Photographic sequence of the leakage test for inorganic PCM composites.

Table 5. Leakage test results of inorganic and organic PCM composites.

Carrier	Material	Composite Mass (Carrier + PCM) (g)	Mass After the Test (g)	Leaked PCM Mass (g)	Retained PCM Mass (g)	Leakage Ratio (%)	PCM Loading Ratio (%)	Heat Amount Retained by 1 g of Carrier (kJ/kg)
Inorganic Material	Vermiculite	2,47 gr	2,02 gr	0,45 gr	0,99 gr	18,2	49	158,59 kJ/kg
	Perlite (expanded)	3,60 gr	2,90 gr	0,7 gr	2,20 gr	19,4	75	518,5 kJ/kg
	Bentonite	9,14 gr	8,81 gr	0,33 gr	4,58 gr	3,6	51	179,07 kJ/kg
	Sepiolite	4,36 gr	3,48 gr	0,88 gr	1,50 gr	20,1	43	125 kJ/kg
Organic Material	Tobacco Leaf (powdered)	1,80 gr	1,58 gr	0,22 gr	0,93 gr	12,2	58	236 kJ/kg
	Black Cumin	7,83 gr	7,50 gr	0,33 gr	2,16 gr	4,21	28	67,5 kJ/kg
	Sawdust	1,81 gr	1,49 gr	0,32 gr	0,47 gr	17	31	76,78 kJ/kg
	Bay Leaf (powdered)	3,25 gr	2,60 gr	0,65 gr	1,85 gr	20	71	436,07 kJ/kg

cumin (28%) and sawdust (31%) showed lower PCM loading ratios among the organic carriers, consistent with their limited absorption observed during impregnation. The relationship between the PCM loading ratio and leakage ratio for both organic and inorganic composites is illustrated in Fig. 5.

According to the graphical results, perlite and bay leaf exhibited the highest PCM loading ratios due to their porous morphology but also displayed the greatest leakage tendencies, indicating weak PCM retention despite high absorption capability.

Conversely, bentonite and black cumin composites demonstrated excellent form stability with low leakage ratios, reflecting strong PCM confinement and structural robustness.

3.3. SEM analysis of PCM composites

Perlite and tobacco leaf composites were selected for SEM and DSC analyses to represent two distinct categories of structural carriers. Expanded perlite exhibited superior PCM absorption behavior, demonstrating the highest PCM loading capacity among all inorganic carriers due to its highly porous and interconnected pore structure. Additionally, due to the fibrous biomass structure of the tobacco leaf, the tobacco composites provided a good level of PCM loading and relatively better form stability, resulting in balanced performance. Therefore, these two materials were chosen as representative samples to investigate the morphology and thermal behavior of PCM-carrier interactions.

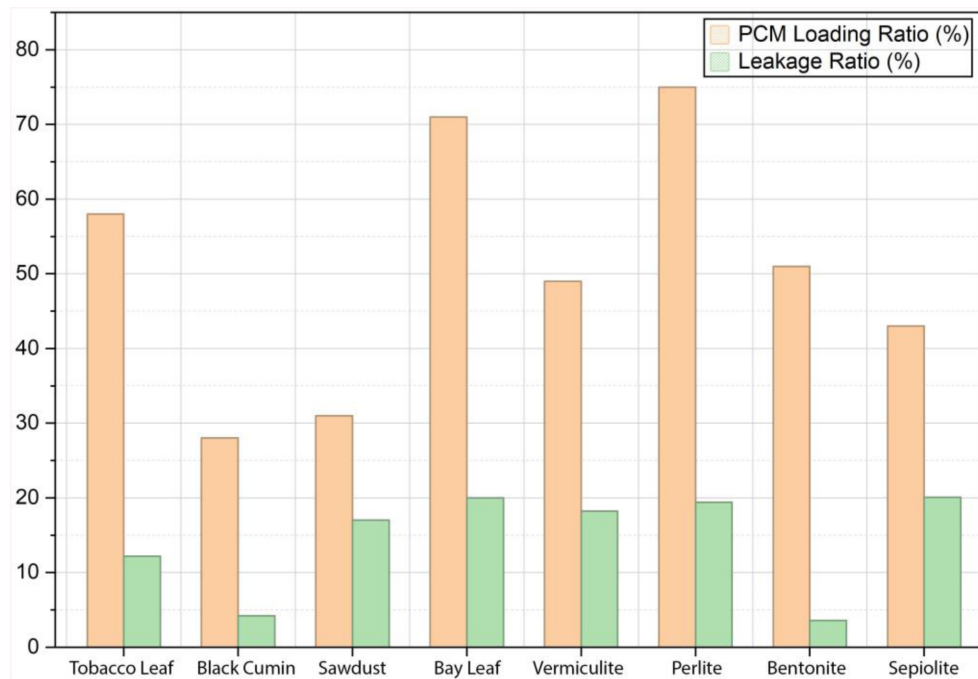


Fig. 5. Comparison of leakage ratio and PCM loading ratio for inorganic and organic PCM composites.

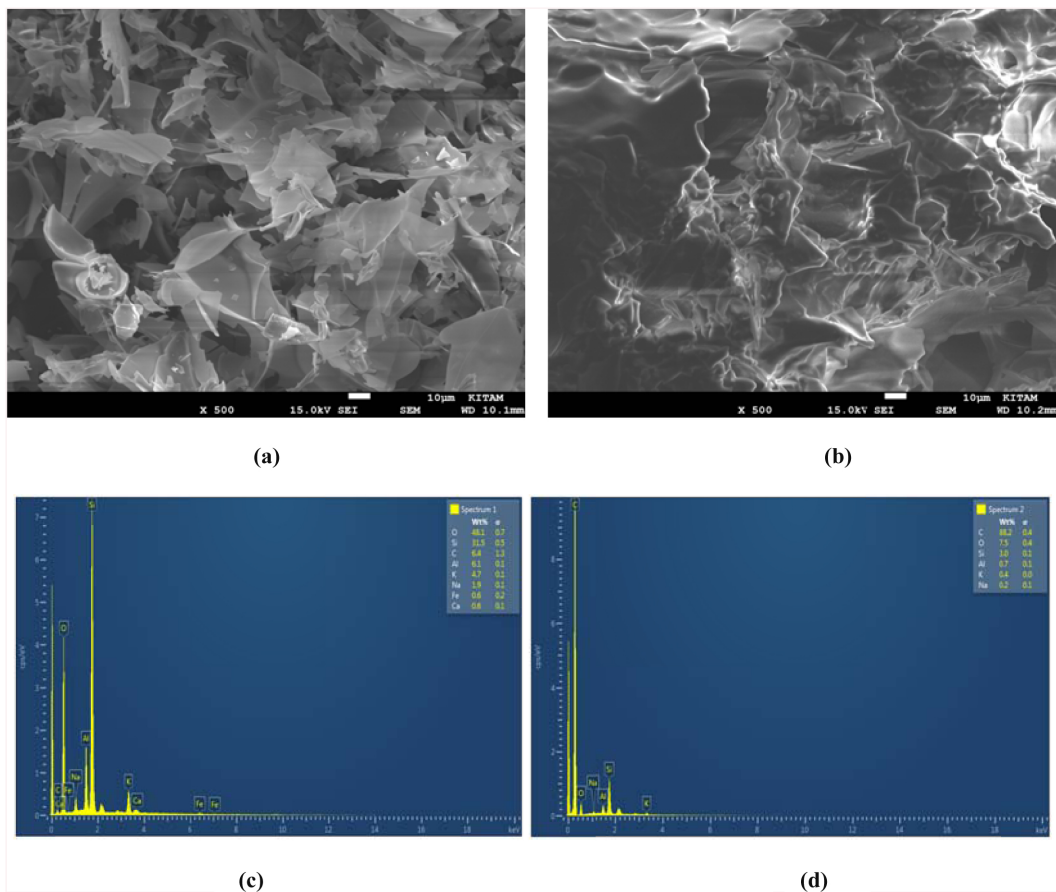


Fig. 6. SEM images of expanded perlite (a), SEM images of perlite/PCM composite (b), EDS analysis of expanded perlite (c), EDS analysis of perlite/PCM composite (d).

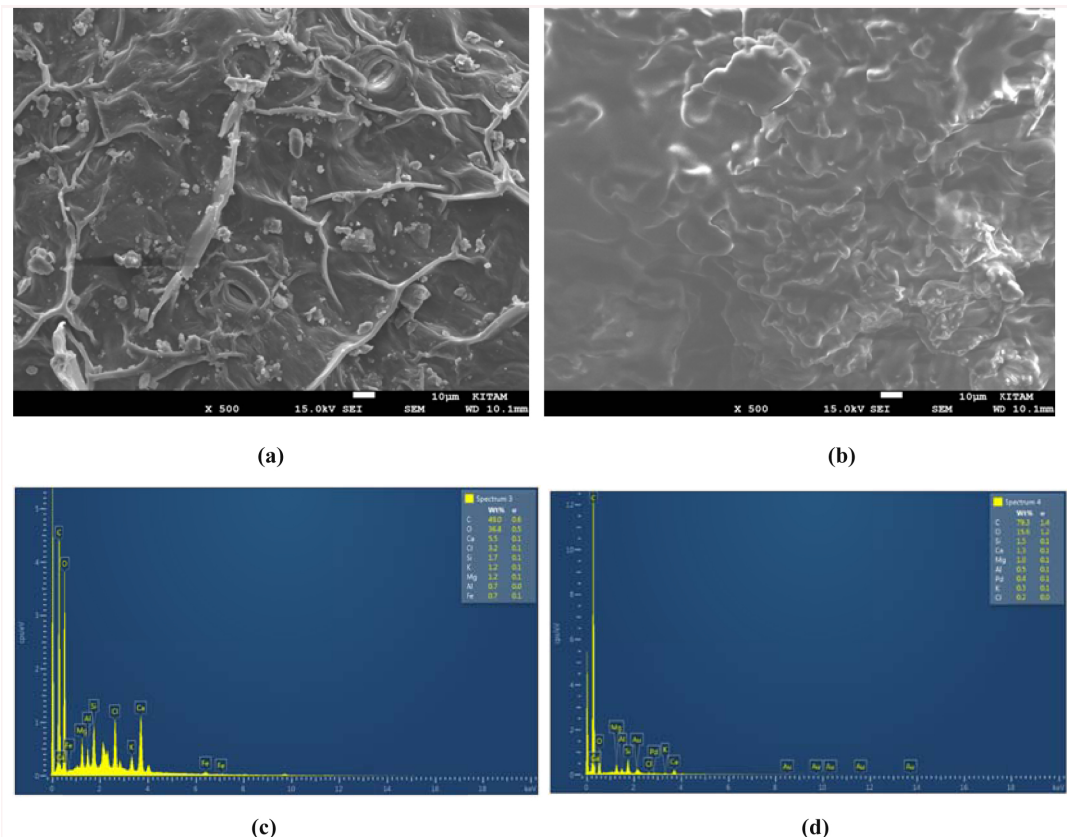


Fig. 7. SEM images of tobacco leaf (a), SEM images of tobacco leaf/PCM composite (b), EDS analysis of tobacco leaf (c), EDS analysis of tobacco leaf/PCM composite (d).

SEM images of the perlite and tobacco samples are presented in Fig. 6 and Fig. 7. Upon examining the SEM images of pure perlite (Fig. 6a), it is observed that the sample exhibits a layered, irregular, and highly porous surface morphology. Distinct voids and sharp-edged structures are noticeable in the pure perlite structure, highlighting the material's porous nature. In the paraffin-impregnated perlite sample (Fig. 6b), the surface appears more compact and partially coated. It is understood that the paraffin spreads across the perlite surface, partially filling the pores and reducing surface roughness. The presence of high levels of oxygen (O) and silicon (Si) elements in the EDS analysis results for both samples confirms the silicate-based structure of the perlite. The significant increase in the carbon (C) content (70%) in the paraffin-impregnated sample indicates that the paraffin was successfully impregnated into the perlite structure. Additionally, the relative decrease in silicon and oxygen content in the impregnated sample can be attributed to the surface being coated with a paraffin layer. When the obtained SEM and EDS results are evaluated together, it is concluded that the paraffin has successfully dispersed within the perlite matrix and a composite structure has formed.

In the SEM image of raw tobacco (Fig. 7a), an irregular, convoluted, and heterogeneous morphology of the leaf surface is observed, whereas in the paraffin-embedded tobacco sample (Fig. 7b), the surface appears smoother and more compact. The fibrous/vascular-like structures and dark regions in the raw tobacco sample represent the leaf's natural surface topography and cellular depressions. It is evident that these natural surface details are largely covered and surface roughness is reduced following the paraffin impregnation process. In EDS analyses (Fig. 7c–Fig. 7d), while carbon and oxygen elements are dominant in both samples, the increased carbon ratio in the paraffin-impregnated sample confirms the hydrocarbon nature of the paraffin.

3.4. DSC analysis of PCM composites

To experimentally evaluate the phase-change behavior and latent heat storage properties of organic and inorganic PCM composites, DSC analysis was performed on representative samples. The DSC thermograms of the expanded perlite/PCM composite, the tobacco leaf/PCM composite, and pure paraffin are presented in Fig. 8, respectively. Both compos-

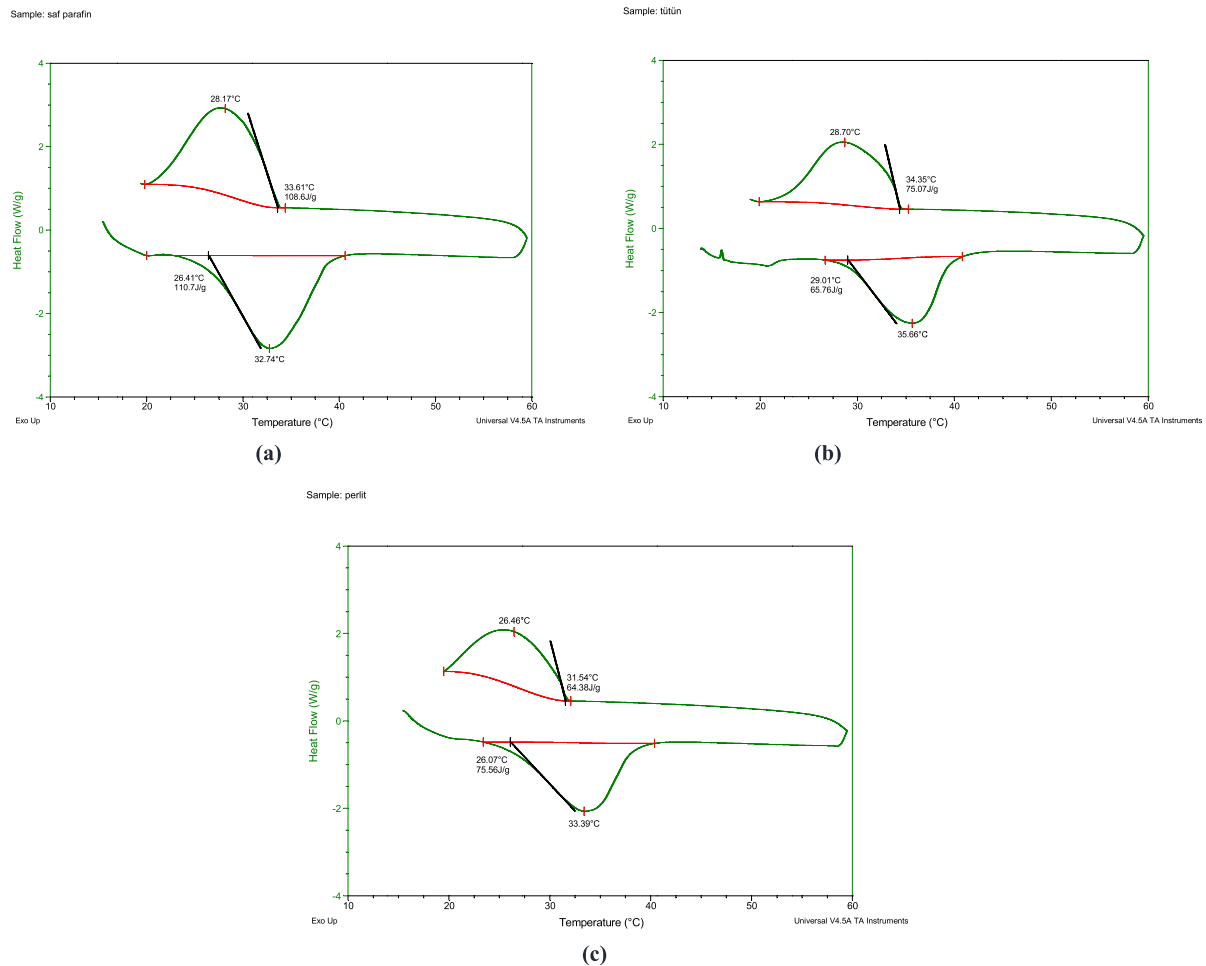


Fig. 8. DSC analysis of paraffin(RT-31) (a), tobacco leaf/PCM composite(b), perlite/PCM composite(c).

ites exhibited distinct endothermic and exothermic peaks associated with the melting and solidification processes of the RT-31 phase change material.

DSC analyses have shown that perlite, tobacco, and pure paraffin samples exhibit different thermal behaviors. An exothermic peak at 26.41 °C and an endothermic peak at 32.74 °C were observed in the perlite sample (Fig. 8c), and these transitions were assessed to be related to surface adsorption/desorption events, structural rearrangements, and moisture removal associated with the porous structure. The latent heat of fusion for perlite was determined to be 75.56 J/g. In the tobacco sample, an exothermic peak at 28.70 °C and an endothermic peak at 35.66 °C were detected (Fig. 8b); this behavior was attributed to the rearrangement of organic components, the removal of volatile components, and structural relaxation processes. The latent heat of fusion of the tobacco was calculated to be 65.76 J/g. In the pure paraffin sample, an exothermic peak at 28.17 °C and an endothermic peak at 32.74 °C were identified; the

endothermic transition, in particular, confirmed the typical phase transition behavior of paraffin (Fig. 8a). Due to paraffin's regular crystalline structure, sharper and more distinct peaks were observed, and its latent heat of fusion was found to be 110.7 J/g. In conclusion, the fact that the endothermic peak temperatures of the samples are close to one another indicates similar low-temperature energy storage behavior; however, it is understood that paraffin, which has the highest latent heat value, is the most suitable material for thermal energy storage applications. Perlite and tobacco, despite having lower latent heat values, have demonstrated potential for use as support materials or in composite PCM systems.

3.5. Life cycle assessment (LCA)

This section of the study aims to evaluate the environmental impacts of mixtures with different content quantities. The simapro software, which includes the ecoinvent database widely used in life cycle as-

Table 6. Material contents selected from the ecoinvent database.

Paraffin	Bentonite	Vermiculite	Wood chips	Expanded perlite
Paraffin {RoW} paraffin production Cut-off, S	Bentonite {RoW} bentonite quarry operation Cut-off, S	Vermiculite {RoW} vermiculite mine operation Cut-off, S	Wood chips, from post-consumer wood, measured as dry mass {RoW} treatment of waste wood, post-consumer, sorting and shredding Cut-off, S	Expanded perlite {RoW} expanded perlite production Cut-off, S

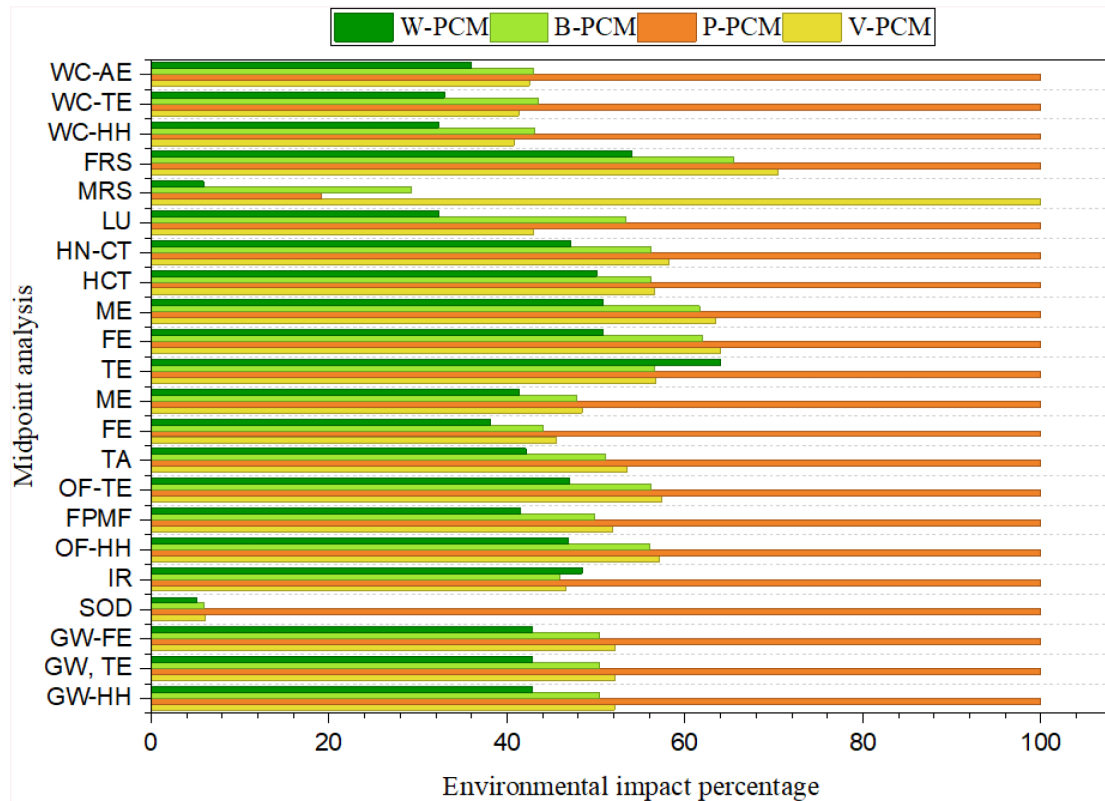


Fig. 9. Results of mid point effect analysis of mixtures (W-PCM: Wood-based PCM mixture, B-PCM: Bentonit-based PCM mixture, P-PCM: Perlite-based PCM mixture, V-PCM: Vermiculite-based PCM mixture, WC-AE: Water consumption, Aquatic ecosystems, WC-TE: Water consumption, Terrestrial ecosystem, WC-HH: Water consumption, Human health, FRS: Fossil resource scarcity, MRS: Mineral resource scarcity, LU: Land use, HN-CT: Human non-carcinogenic toxicity, HCT: Human carcinogenic toxicity, ME: Marine eutrophication, FE: Freshwater eutrophication, TE: Terrestrial ecotoxicity, TA: Terrestrial acidification, OF-TE: Ozone formation terrestrial ecosystems, FPMF: Fine particulate matter formation, OF-HH: Ozone formation, human health, IR: Ionizing radiation, SOD: Stratospheric ozone depletion, GW-FE: Global warming, freshwater ecosystems, GW,TE: Global warming, terrestrial ecosystems, GW-HH: Global warming, human health).

sessments in the field of architecture and building materials, was chosen. The ReCiPe 2016 Endpoint (H) V1.11 / World (2010) H/A method was applied to evaluate the comparative environmental impacts of the mixtures. The ReCiPe method analyzes environmental impacts across multiple parameters and classifies the analyses into a “midpoint” and three main “endpoint” categories (Human health, Ecosystems, Resources). Since the total quantities of the analyzed mixtures differed, the mixtures were normalized based on their content ratios per 1000 g to perform comparative analyses. In the study, since data for Turkey in the ecoinvent database was limited, the closest contents to the materials used in

the mixture were selected for analysis (Table 6). Due to limitations in the Ecoinvent database, the “post-consumer wood chips” dataset was chosen as the closest approximation for the experimental wood chip material used in this study. The wood chips used in the impregnation experiments were collected as waste material from the university workshop. The materials used in the comparative evaluation are listed in the table below.

According to the median point analysis results (Fig. 9), perlite-pcm (P-PCM) mixtures had the highest environmental impact in almost all categories, while wood-based mixtures (W-PCM) emerged as the mixtures with the lowest impact. Particularly

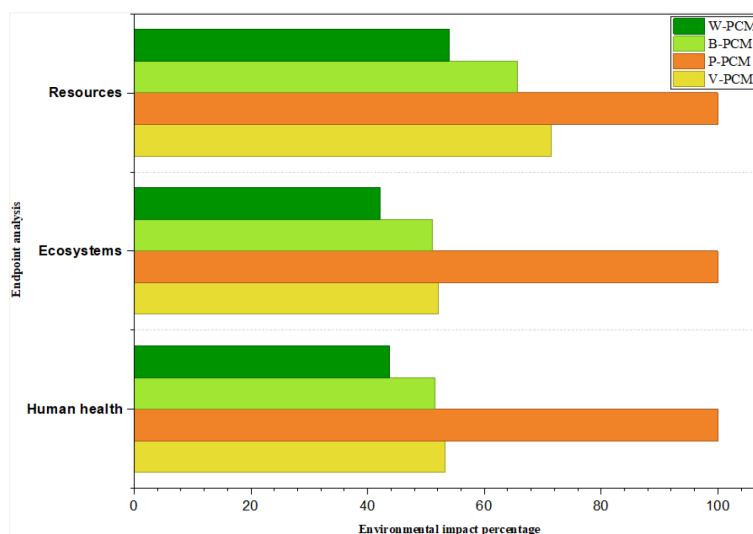


Fig. 10. Results of endpoint effect analysis of mixtures (Human Health, Ecosystems, Resources categories, W-PCM: Wood-based PCM mixture, B-PCM: Bentonite-based PCM mixture, P-PCM: Perlite-based PCM mixture, V-PCM: Vermiculite-based PCM mixture).

in the “Stratospheric ozone depletion” impact category, the perlite-containing mixture showed a clear increase in environmental impact, with a 94% difference compared to the vermiculite-containing mixture (V-PCM) that followed immediately after it. In general, in other impact categories, perlite mixtures are followed by vermiculite, bentonite, and wood-based mixtures. However, significant differences that alter this ranking are noticeable in some categories. For example, in the “Mineral resource scarcity” category, the vermiculite-containing mixture emerged as the mixture with the most harmful effects, with a clear difference compared to other mixtures.

In endpoint analyses (Fig. 10), where midpoint analyses are divided into three main effect classes, results similar to midpoint analyses are observed. In all categories, the perlite mixture was identified as the most harmful category, while the wood mixture was identified as the least harmful content. This ranking occurred in a similar manner to the ranking of mixtures containing high levels of pcm to low levels of pcm, such as perlite, vermiculite, bentonite, and wood. The percentage differences between the mixture with the highest harmful effect and the mixture with the lowest harmful effect under the headings ‘Human health’ and ‘Ecosystems’ were similar, at around 56% and 58%, respectively. In the ‘Resources’ categories, this increase was 46%, which was lower than in other categories. The final point analysis graph is shown below.

All these results show that as the PCM quantities in the mixtures are associated with increased environmental impacts. Furthermore, it is observed that the mixtures containing natural and organic materials

such as wood, along with PCM ratios, have the least harmful effects. The wood material in the database was selected based on certain processes that take environmental harmful effects into account. Environmental harmful effects will be further reduced in wood materials used directly as waste. As a result of the LCA analysis, it was determined that the wood mixture with low PCM and natural organic content has less environmental harmful effects compared to other contents.

4. Discussion and conclusion

The primary aim of this study was to experimentally compare the absorption and leakage performance of different organic (tobacco, sawdust, bay leaf, black cumin) and inorganic (vermiculite, perlite, bentonite, sepiolite) carrier materials for phase change material (PCM) integration, and to identify suitable carriers for potential application in building materials.

The experimental results revealed that the microstructure of the carrier material plays a decisive role in determining both PCM retention capacity and form stability. Perlite and bay leaf, due to their structural characteristics, exhibited the highest PCM impregnation capacities ($C = 80\%$ and $C = 78\%$, respectively) and mass percentage gains (414% and 364%). However, these materials also showed the highest leakage ratios (approximately 19–20%), indicating limited shape stability. In contrast, bentonite, despite its relatively lower impregnation capacity ($C = 53\%$), demonstrated the lowest leak-

age ratio (3.6%), confirming excellent form stability. Similarly, black cumin also displayed low leakage (4.2%) and good structural integrity. Overall, materials with highly porous structures (e.g., perlite and bay leaf) provided greater energy storage potential, while those with layered or closed-pore structures (e.g., bentonite) offered better form stability but lower storage capacity. This highlights the need to achieve a balance between thermal energy storage capacity and leakage resistance in the design of PCM-based composite materials. However, findings from SEM, EDS, and DSC analyses indicate that the phase change material (PCM) is successfully absorbed and retained within the carrier material structure. LCA analysis results show that environmental impacts increase as the PCM content in mixtures increases. Among inorganic components, the highest environmental impact was observed in mixtures containing perlite. Organic materials, particularly in mixtures containing wood, were found to reduce environmental impacts. Wood is considered a material that can be recycled after use. The environmental impacts of wood used as direct waste will be even lower.

In conclusion, the findings indicate that the interaction between PCM and the carrier material is primarily governed by pore size, surface energy, and structural organization. Materials with large and open pores absorbed higher amounts of PCM, but during phase transition, the liquid phase tended to migrate to the surface, resulting in increased leakage. Conversely, the layered microstructure of bentonite effectively confined the PCM within interlayer spaces, significantly reducing leakage. Therefore, minerals with lamellar absorption structures, such as bentonite, can be considered promising carriers for the development of form-stable PCM composites. However, to enhance the overall energy storage capacity, future work should focus on controlled modification of pore structures, surface functionalization, or the design of hybrid carrier systems combining the advantages of both open-pore and layered structures. In general, this study demonstrates that the selection of an appropriate carrier material, one that maintains an optimal balance between high latent heat storage and structural stability, is critical for improving the applicability of PCMs in building materials. The results contribute valuable insights toward the development of sustainable, energy-efficient construction materials incorporating phase change technology.

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.

Conflict of interest

The authors declare no conflict of interest.

Author's contributions

All of the authors have contributed equally to the article. Further, all of the authors have validated and approved the final manuscript.

Data availability statement

All graphs and data obtained or generated during the investigation appear in the published article.

Ethics

There are no ethical issues with the publication of this manuscript.

Abbreviations

C	impregnation capacity
FE	freshwater eutrophication
FPMF	fine particulate matter formation
FRS	fossil resource scarcity
GWFE	global warming, freshwater ecosystems
GWHH	global warming, human health
GWTE	global warming, terrestrial ecosystems
HCT	human carcinogenic toxicity
HNCT	human non-carcinogenic toxicity
IR	ionizing radiation
LCA	life cycle assessment
LU	land use
ME	marine eutrophication
MPG	mass percentage gain
MRS	mineral resource scarcity
PCM	phase change material
OFHH	ozone formation, human health
OFTE	ozone formation terrestrial ecosystems
SOD	stratospheric ozone depletion
TA	terrestrial acidification
TE	terrestrial ecotoxicity

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Appendix A

Units used in the study.	
Unit	Meaning
g	gram
kg	kilogram
°C	degree Celsius
min	minute
kJ/kg·K	specific heat capacity
kJ/kg	specific enthalpy
kg/l	density
W/(m·K)	thermal conductivity