# Use of Phase Change Materials in Wood and Wood-Based Composites for Thermal Energy Storage: A Review

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Using phase change materials (PCMs) is an efficient solution for reducing energy consumption in buildings. These materials have a large capacity for storing thermal energy, making them an appealing option for energy management purposes. Phase change materials have been successfully incorporated into various construction materials such as concrete, brick, or plaster. The primary objective of this review is to examine previous studies conducted on the application of PCMs in wood. The initial section presents an overview of the direct impregnation techniques utilized for wooden materials. This is followed by a discussion on the implementation of macroencapsulated PCMs in wooden structures that are typically present in residential buildings. In addition, the use of shape-stabilized PCM/wood composites, preventing potential leaks during the phase change transition, is explored. Finally, patents related to the use of PCMs in wood are described. Future challenges include the incorporation of PCMs into wood composites to improve their thermal properties. This literature review shows that there is a gap in knowledge regarding the utilization of phase change materials in wood-based panels such as oriented strandboards, fiberboards, and particleboards. This provides an opportunity for future research to improve the performance of the products manufactured by the wood-based panels industry.

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## INTRODUCTION

In recent times, there has been a growing global concern about managing energy consumption, as fossil fuels are non-renewable (Solgi *et al.* 2019). Buildings account for the consumption of 40% of the global energy resources, and the energy loss caused by building envelopes is a significant contributor to this (Hu and Yu 2019). One possible solution to meet energy demands is to transition to renewable sources that can satisfy some of the current energy requirements. An alternative approach to the management of energy consumption involves the utilization of systems that enable the storage of thermal energy (Li *et al.* 2019). Such systems can be categorized into three groups: sensible, chemical, and latent (Yang *et al.* 2020b). The latter presents upsides associated with its capacity to retain substantial heat quantities at a consistent temperature, its elevated energy density, and the fact that it may incur minimal expenses (Alí 2019). Phase change materials (PCMs) are widely used as latent energy storage systems. They possess a considerable capacity for storing energy, good thermal reliability (which involves a satisfactory efficiency of the material after many cooling and heating cycles), stability, and high energy density. Phase change materials are inexpensive, have low-temperature fluctuations when phase changes occur, and are generally non-toxic (Wei *et al*. 2014; Kumar *et al*. 2017; Ma *et al.* 2017; Liu *et al.* 2020).

Phase change materials possess the unique ability to absorb, retain, and discharge energy through latent heat (Liu *et al.* 2016; Lin *et al.* 2018; Vennapusa *et al.* 2020). In a latent heat storage system, typically involving a transition between solid and liquid states, energy is retained during the melting of PCM and subsequently liberated upon its solidification (Jeong *et al.* 2012; Khan *et al.* 2016; Safari *et al.* 2017). Phase change materials can be classified into two categories: organic and inorganic, depending on their composition and source. According to Kośny (2015), paraffin and fatty acids are frequently utilized in the first category, while hydrated salts are commonly used in the second category. In general, inorganic compounds have about twice the storage capacity of organic compounds. However, they are usually very corrosive and suffer from overcooling (Rathod and Banerjee 2013). For this reason, many researchers have focused on the study of organic PCMs. There is another type of PCMs called eutectics. These are made up of two or more chemical components that undergo phase change together (Kośny 2015). These PCMs have a high phase change enthalpy, excellent thermal stability, and are generally non-toxic (Kant *et al.* 2016). One problem with PCMs is their tendency to leak during phase change, which can lead to losses (Wan *et al.* 2019). There are two ways to address this problem: by encapsulating the PCM through macro or microencapsulation, or by creating a shape-stable wood/PCM composite through the formation of a micro or macro scale network that traps the material (Das *et al.* 2020).

Over the last forty years, the incorporation of PCMs has been studied to improve the thermal behavior of different materials frequently employed in construction, such as brick (Fraine *et al.* 2019; Gao *et al.* 2020; Saxena *et al.* 2020), cement (Laaouatni *et al.* 2017; Frazzica *et al.* 2019; Guardia *et al.* 2019), and gypsum (Kusama and Ishidoya 2017; Lachheb *et al.* 2017; Wi *et al.* 2019). There have been few studies that have explored the use of wood for PCM integration. Wood is a renewable resource and the integration of PCMs into its structure could lead to the elaboration of bio-based materials for construction purposes (Nazari *et al.* 2020). To be more specific, there is no published research on the incorporation of PCMs into wood-based panels such as oriented strand boards, fiberboards, or particleboards. No information is available regarding the possible interaction between the PCMs, adhesive, and wood particles. This review paper discusses the most recent advancements in using PCMs in wood and wood-based composites for thermal energy storage applications. Additionally, it highlights the primary obstacles and potential for progress in the development of wood/PCM composites.

## USE OF PHASE CHANGE MATERIALS IN WOOD AND WOOD-BASED COMPOSITES

Various research studies have explored diverse techniques for the inclusion of PCMs into wood-based products. One option is to directly impregnate the material, but this can lead to leakage when the phase changes occur, as noted by Singh *et al.* (2021). To prevent this from occurring, the PCM can be microencapsulated and then impregnated, as seen in studies by Borreguero *et al.* (2011) and Alva *et al.* (2017). Another method involves macroencapsulation of the PCM and its subsequent inclusion in wooden housing structures. Additionally, the formation of shape-stabilized wood/PCM composites is another approach to consider.

## Direct Impregnation of Phase Change Materials in Wood

Figure 1 provides a concise overview of the various methods used for direct PCM impregnation in wood. Additionally, it highlights the specific types of PCM utilized in each respective section.

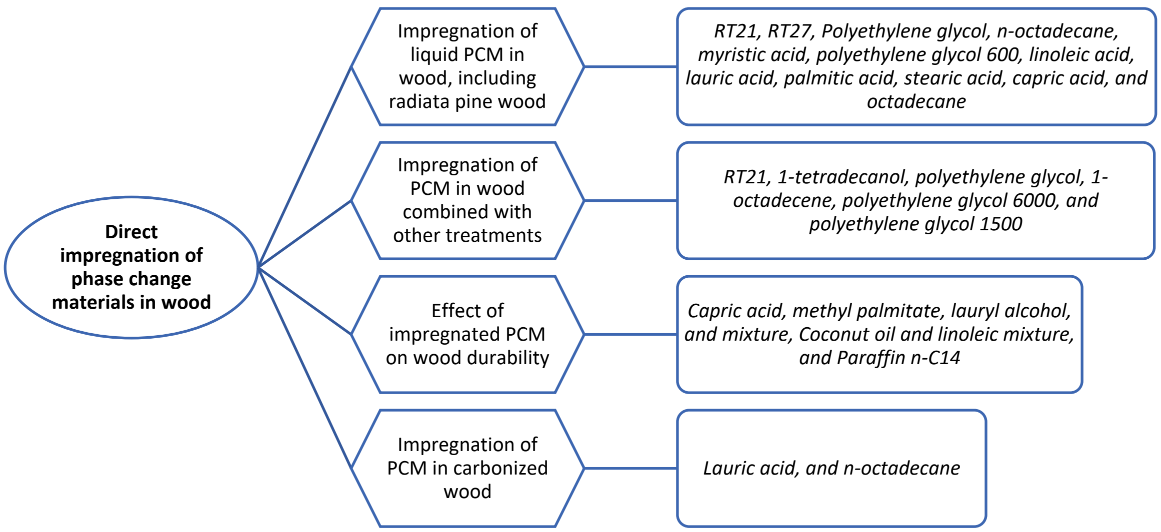


**Fig. 1.** Summary of the direct PCM impregnation methods in wood

### *Impregnation of liquid PCM in wood*

Recently, Barreneche *et al.* (2017) incorporated a paraffinic PCM (RT21 and RT27) in black alder wood to provide a higher thermal mass and therefore better temperature regulation between day and night. The maximum latent heat of fusion reported by the authors was 20.6 J/g for a PCM concentration (wt. %) of 29.9%. Thermal mass pertains to the capacity of a material to absorb, retain, and discharge thermal energy in response to temperature variations. On the other hand, latent heat is the amount of heat or energy required for a phase change to occur without a change in the temperature. Li *et al.* (2016) impregnated green Douglas-fir wood with polyethylene glycol (PEG) at atmospheric pressure to produce a material with energy storage capacities. The results showed that the samples had a fusion temperature of 26.7 °C and a latent heat of fusion of 73.6 J/g. According to thermogravimetric analysis (TGA) and thermal cycling tests (400 melting and solidification cycles), the composite displayed good stability and satisfactory thermal and chemical reliability. The authors suggested that the resulting composite was satisfactory for heat storage applications in wood-based structures. Recently, Nam *et al.* (2022) used balsa wood and cork as matrix materials for n-octadecane impregnation. The objective was to improve the thermal properties of these materials. The results indicated that balsa wood and cork had a latent heat of fusion of 49.7 J/g and 131.2 J/g respectively. The authors determined that the hydrophilic surface of composite materials shifts to hydrophobic as a consequence of filling the porous structure with PCM, based on their measurement of the contact angle at the surface.

Liu *et al.* (2021) explored the feasibility of using myristic acid, paraffin, and polyethylene glycol (PEG) as PCMs for thermal energy storage. The researchers used the vacuum impregnation method in balsa wood. The adsorption capacity of PEG in the wood samples was the lowest. On the other hand, paraffin showed the highest latent heat of fusion with a value of 181.9 J/g. Out of the three composites tested, the myristic acid/wood composite displayed superior thermal reliability and reusability. Nazari *et al.* (2022b) used a blend of fatty acids as a bio-based PCM to impregnate Scots pine and European beech wood samples. The measured latent heat of fusion was 42.4 and 27.0 J/g for the impregnated Scots pine and beech samples, respectively. On the other hand, untreated beech wood exhibits thermal conductivity that is twofold greater than that of untreated pine, owing to its elevated density. After the impregnation process, thermal conductivity increased for both. The impregnated samples showed a specific heat capacity of 3.8 J/g K for beech samples and 5 J/g K for pine samples. The conclusion reached by the authors is that the latent heat of the impregnated samples is dependent on the latent heat of the PCM and its quantity. If the amount of PCM incorporated in the wood structure is high, the latent heat of the composite formed will be higher. Sun *et al.* (2021) impregnated four different fatty acids (FA) in delignified platane wood (DW). The PCMs were added to the supporting material through vacuum impregnation. Using stearic acid as an impregnated PCM, the composites reached the highest latent heat of fusion value at 162.3 J/g. The highest rate of FA impregnation into the DW reached 79.7 (wt. %) using lauric acid as an impregnant. Based on Fourier-transform infrared spectroscopy (FTIR) tests, it was found that DW and FA only have a physical interaction. Additionally, TGA tests demonstrated that the composites possess good thermal stability.

Amini *et al.* (2022) utilized vacuum-pressure impregnation to create a phase change composite using Scots pine wood and various concentrations of capric acid (CA). The resulting composites had a latent heat of fusion of 70.5 J/g and a fusion temperature of 28.4 °C. No significant difference in bending strength was found between the treated samples and those that were not impregnated. However, the compression strength results of the treated sample were superior to those of the control sample. In conclusion, Scots pine impregnated with CA is suitable for thermal regulation in building applications. Similarly, Grzybek *et al.* (2023) evaluated the potential of a capric acid and stearic acid mixture as a bio-based PCM to improve the thermal properties of Norway spruce wood. The PCM mixture was used in different concentrations and impregnated through a vacuum-pressure method. The results showed an increase in density and perpendicular to the grain compressive strength in the impregnated wood. This is because the impregnation process was successful, and all the pores in the wood structure were filled. The highest achieved retention was 267 kg/m$^3$ with a latent heat of fusion of 70.5 J/g. According to the authors, the acid mixture has the potential to enhance the thermal properties of wood. It is important to mention that there is a risk of PCM leakage during phase transitions, which has been highlighted in much of the research discussed above.

*Impregnation of PCM in radiata pine wood*

Radiata pine is a commonly grown and utilized wood in Chile. Vasco *et al.* (2018) carried out an exploratory study to evaluate the possibility of pressure-impregnating radiata pine wood using octadecane. They found that the amount of PCM impregnated in wood increased with an increase in pressure. The PCM content increased from 50 to 66% when the pressure increased from 1 to 3 bars. The effects of PCM content on the thermal properties of radiata pine wood were highly variable and therefore inconclusive. However, when the impregnated PCM content increased, the thermal conductivity and heat capacity also increased. Heat capacity is the quantity of heat necessary to elevate the temperature of a substance by 1 °K.

Fuentes-Sepúlveda *et al*. (2020) conducted a thermal characterization study on radiata pine samples impregnated with a PCM, specifically octadecane. The study assessed the impacts of both temperature and anatomical orientation of the samples. The impregnated wood exposed to heat acquired thermal properties with similar behavior to the PCM used. Thermal conductivity exhibited greater values in the tangential and radial directions of wood compared to the longitudinal direction. Based on the results of the differential scanning calorimetry (DSC) analysis, the authors found that the impregnated wood had a latent heat of fusion of 122 J/g. This indicates that radiata pine impregnated with a PCM can store latent heat, making it a viable option for use in building applications.

Using another approach, Saavedra *et al.* (2021) evaluated the mechanical properties of PCM-impregnated radiata pine wood. The samples were impregnated with octadecane as PCM using the vacuum-pressure method. Their mechanical properties were then determined and compared to those of non-impregnated samples. The tensile properties of both the non-impregnated and PCM-impregnated samples showed similar behavior. The compression strength results showed a similar behavior, to the exception of the tangential direction where the Young's modulus increased for PCM-impregnated samples. On the other hand, the bending properties of the wood impregnated and non-impregnated samples were alike.

*Impregnation of PCM in wood combined with other treatments*

Md Said and Mohd Tohir (2020) investigated the viability of employing a UV-curable coating to improve the retention of a PCM mixture and paraffin wax impregnated in pine wood. The authors used vacuum impregnation, incorporating up to 42% (wt. %) of PCM in the wood samples. Two types of coatings were used: one was made of epoxy acrylate lacquer alone, while the other was a combination of epoxy acrylate and ammonium polyphosphate (APP). This research concluded that a UV coating is not efficient to prevent PCM losses at temperatures up to 50 °C. Therefore, the use of another type of coating that prevents PCM leakage during phase transitions is necessary. This is one of the main problems to avoid when it is desired to incorporate PCM into the anatomical structure of wood. Yang *et al.* (2020a) developed a wood-based composite with PCM using 1-tetradecanol (TD) as an impregnant, with self-cleaning properties for thermal energy storage. Before impregnation, the lignin was removed to generate more empty spaces in the wood. This coating provides protection against PCM leakage. It also results in a high contact angle of 155°, which reduces the interaction with liquid water in wet environments. In addition, the resulting composite showed a high latent heat of fusion of 125.4 J/g (pure TD had a latent heat of fusion of 209.2 J/g), excellent thermal reliability and stability, and self-cleaning properties. Thus, the material obtained is a viable alternative for applications involving thermal storage.

In another study, Xu *et al.* (2020) fabricated a composite incorporating silica-stabilized PEG into Southern pine sapwood. The results showed a latent heat of fusion of 46.7 J/g. The thermal conductivity of the modified wood samples was slightly higher in comparison to the non-modified samples. In addition, a thermal cycling test showed excellent thermal reliability. The thermal reliability of PCMs is usually evaluated by studying their thermal properties after accelerated thermal cycles. This evaluation aimed to check their suitability for long-term utilization in latent heat thermal energy storage applications (Yang *et al.* 2019b). These findings demonstrate that wood impregnated with PCM might be a viable building material for storing thermal energy.

Yang *et al.* (2019a) impregnated delignified balsa wood with a mixture of 1-tetradecanol and $Fe_3O_4$ nanoparticles to obtain a magnetic wood-based composite with a high latent heat of 179.0 J/g. In addition, the nanoparticles used provided the composite with magnetic properties and improved its capacity to convert solar energy into thermal energy. Qiu *et al.* (2020) impregnated veneer samples of balsa wood with a copolymer solution of styrene (St), butyl acrylate (BA), and 1-octadecene (ODE). The aim was to obtain a flexible transparent wood (TW) material characterized by reversible optical traits. Using a 5% ODE content, the resulting composite proved to have excellent thermo-reversible transparency and the capability to switch between different levels of haze. Also, the authors concluded that the composite showed excellent thermal resistance with a thermal conductivity of 0.2 W $m^{-1}$ $K^{-1}$. This feature made it suitable for better thermal insulation efficiency. Similarly, Xia *et al.* (2021) used an epoxy resin and PEG mixture to impregnate delignified balsa wood. The aim of the authors was to develop a novel transmittance energy storage wood composite. Differential scanning calorimetry results showed an enhancement in energy storage efficiency as a greater quantity of PEG was integrated, resulting in a high latent heat of 134.1 J/g. The highest optical transmittance value of the composite was 80.9%. This innovative wood composite is biodegradable and can enhance the comfort of living spaces and boost the energy efficiency of buildings. Yang *et al.* (2018) used a thermochromic compound (TC) with 1-tetradecanol as PCM and delignified wood to develop a thermochromic delignified wood composite. Delignification increases the porosity of wood by creating more empty spaces. This improves its permeability, allowing for the incorporation of more PCM during the impregnation process. The resulting composite showed a high latent heat of 104.9 J/g, excellent thermal stability, and good reliability. The color change of the composite material permitted to monitoring of the temperature and phase change progress. Therefore, the authors concluded that these have good reversible thermochromic ability.

Chen *et al.* (2022) fabricated a novel composite material made of delignified balsa wood and polyethylene glycol 6000 by vacuum impregnation. Boron nitride (BN) was added to this mixture to enhance the thermal conductivity. The results revealed that the incorporation of 33% by weight of BN into the composite, led to an increase in its thermal conductivity in contrast to samples devoid of BN. The latent heat of fusion was 209.3 J/g reflecting a 7.2% increase in comparison to that of pure PEG. Moreover, the composite demonstrated elevated mechanical strength and flexibility under thermal conditions. Similarly, Shi *et al.* (2022) used PEG as PCM to impregnate wood modified with boron nitride, polyethylenimine and polypyrrole. These modifications were made to improve light absorption as well as thermal conductivity, and to prevent leakage in wood samples. The composite material exhibited a phase change temperature of 62.2 °C, accompanied by a latent heat of 159.7 J/g at a PEG encapsulation ratio of 78.1%. The encapsulation ratio is the percentage of PCM material encapsulated within the wood. The composite showed an increased thermal conductivity of up to 26 times that of the wood species used. Using balsa wood, Lin *et al.* (2021) developed a flexible wood-based PCM. Furthermore, graphene was incorporated to increase the thermal properties of the composite, specifically thermal conductivity. The results showed a latent heat of fusion of 64.3 J/g in the resulting material. The introduction of graphene led to a notable enhancement in thermal conductivity, approximately a fourfold increase in comparison to untreated wood. Furthermore, the resultant composite displayed commendable softness and flexibility when heated. Li *et al.* (2022) used a different method of PCM incorporation. They introduced a stable PEG-based energy storage polymer into delignified poplar wood using a high-temperature immersion method. According to the findings, the thermal conductivity of the PCM-impregnated wood increased by 190% compared to its original state. Additionally, the composite had a latent heat of fusion of 25.1 J/g. However, the mechanical tests revealed that the PCM-impregnated wood experienced a significant decrease in its mechanical properties.

*Effect of impregnated PCM on wood durability*

Some researchers focused on the behavior of PCM-impregnated wood against natural decay agents. Palanti *et al.* (2022) studied the resistance of Scots pine wood against biological deterioration subsequent to its impregnation with four distinct Bio-PCMs (capric acid, methyl palmitate, lauryl alcohol, and a mixture of coconut oil fatty acids, and linoleic acid) to termites, beetles, and mold fungi. The wood impregnation was conducted within an oven employing a vacuum of 850 mbar at a temperature of 45 °C over 3 hours. Biological tests revealed that bio-PCMs demonstrated resistance against newly hatched termite larvae. The bio-PCMs evaluated did not prevent discoloration caused by mold fungi. Moreover, mold growth was directly related to moisture and temperature levels. Similarly, Nazari *et al.* (2022a) evaluated the thermal behavior and the potential susceptibility to mold-induced discoloration of three thermally enhanced wood species (Scots pine, beech, and spruce) containing a blend of coconut oil and linoleic acid as PCM. The incorporation of PCM into wood samples resulted in significant thermal mass improvements, especially in Scots pine, which presented the highest latent heat of 70 J/g. Modified beech wood had higher thermal conductivity than the other impregnated samples. The mold susceptibility tests showed that wood/PCM samples exhibited reduced susceptibility to discoloration caused by mold in comparison to untreated wood. Can *et al.* (2023) studied the behavior of Oriental spruce sapwood impregnated with different commercial paraffins used as PCM against white and brown rot fungi. Results showed that samples impregnated with PCMs were resistant to fungus. Upon exposure to white rot fungus, the mass loss was between 2.0% and 4.7%, while brown rot fungus caused a mass loss of 3.0% to 8.2%. Both white and brown rot fungi caused a mass loss of 22.8% and 22.6% in the control sample, respectively. According to the authors, the enhancement in resistance against wood-rotting fungi can be attributed to the establishment of a barrier through paraffin, which hinders the infiltration of fungal hyphae into the wood's anatomical structure.

*Impregnation of PCM in carbonized wood*

Yang *et al.* (2019c) evaluated the impregnation process of delignified and carbonized wood using lauric acid as a PCM. The composite showed a latent heat of 178.0 J/g with an encapsulation ratio higher than 80%. Thermal cycle tests showed a composite with excellent thermal reliability and good thermal stability. Chen *et al.* (2019) prepared a phase change composite using porous carbonized wood and n-octadecane as PCM. Furthermore, a layer of graphite was applied to the composite to mitigate any potential leakage. The study showed that the use of graphite led to a significant increase of 143% in thermal conductivity. The composite had a maximum latent heat of 226.2 J/g. Recently, Sulaiman and Amini (2022) mentioned the potential of biomass materials other than wood in the form of carbon.

**Table 1.** Summary of Studies Carried-out on the Impregnation of Phase Change Materials in Wood

| PCM | Support Material | Method Used | Fusion Temperature of Composite (°C) | References |
|---|---|---|---|---|
| Impregnation of liquid PCM in wood | | | | |
| RT21 and RT27 | Black alder wood | Impregnation | 21 and 27 | (Barreneche *et al*. 2017) |
| Polyethylene glycol | Douglas fir wood | Impregnation | 27 | (Li *et al*. 2016) |
| n-octadecane | Balsa and cork wood | Vacuum impregnation | 23 | (Nam *et al*. 2022) |
| Myristic acid, paraffin, and Polyethylene glycol | Balsa wood | Impregnation | 55, 60 and 55 | (Liu *et al*. 2021) |
| Polyethylene glycol 600, linoleic acid and mixture | Scots pine and beech wood | Vacuum-pressure impregnation | 25 | (Nazari *et al*. 2022b) |
| Lauric acid, myristic acid, palmitic acid and stearic acid | Platane wood | Vacuum impregnation | 42, 53, 62 and 67 | (Sun *et al*. 2021) |
| Capric acid | Scots pine wood | Vacuum-pressure impregnation | 28 | (Mohamad Amini *et al*. 2022) |
| Capric acid and stearic acid mixture | Norway spruce wood | Vacuum-pressure impregnation | 25 | (Grzybek *et al*. 2023) |
| Impregnation of PCM in radiata pine wood | | | | |
| Octadecane | Radiata pine wood | Pressure impregnation | 28 | (Vasco *et al*. 2018) |
| Octadecane | Radiata pine wood | Pressure impregnation | 26 | (Fuentes-Sepúlveda *et al*. 2020) |
| Octadecane | Radiata pine wood | Pressure impregnation | - | (Saavedra *et al*. 2021) |
| Impregnation of PCM in wood combined with other treatments | | | | |
| RT21 | Pine wood | Vacuum impregnation | 21 | (Md Said and Mohd Tohir 2020) |
| 1-Tetradecanol | Basswood slices | Vacuum assisted infiltration | 37 | (Yang *et al*. 2020a) |
| Polyethylene glycol | Southern pine wood | Vacuum impregnation | 25 | (Xu *et al*. 2020) |
| 1-Tetradecano | Balsa wood | Impregnation | 36 | (Yang *et al*. 2019a) |
| 1-Octadecene | Balsa wood | Impregnation | - | (Qiu *et al*. 2020) |
| Polyethylene glycol | Balsa wood | Impregnation | 31 | (Xia *et al*. 2021) |

| | | | | |
|---|---|---|---|---|
| 1-tetradecanol | Poplar wood slices | Vacuum assisted impregnation | 35 | (Yang *et al*. 2018) |
| Polyethylene glycol 6000 | Balsa wood | Vacuum impregnation | - | (Chen *et al*. 2022) |
| Polyethylene glycol | Balsa wood | Vacuum impregnation | 62 | (Shi *et al*. 2022) |
| Polyethylene glycol 1500 | Balsa wood | Impregnation | 34 | (Lin *et al*. 2021) |
| Polyethylene glycol | Poplar wood | High temperature immersion | 26 | (Li *et al*. 2022) |
| Effect of impregnated PCM on wood durability | | | | |
| Capric acid, methyl palmitate, lauryl alcohol, and mixture | Scots pine wood | Impregnation | - | (Palanti *et al*. 2022) |
| Coconut oil and linoleic mixture | Scots pine, beech and spruce wood | Vacuum-pressure impregnation | 24 | (Nazari *et al*. 2022a) |
| Paraffin n-C14 | Oriental spruce wood | Vacuum impregnation | 21 | (Can *et al*. 2023) |
| Impregnation of PCM in carbonized wood | | | | |
| Lauric acid | Carbonized wood | Impregnation | 41 | (Yang *et al*. 2019c) |
| n-octadecane | Carbonized wood | Impregnation | 28 | (Chen *et al*. 2019) |

These materials are an interesting option because they are renewable and cost-effective. Some pyrolyzed materials used to create composite PCMs are waste sugar beet pulp, corn straw, and wood.

The most studied method for incorporating PCM into wood is through direct impregnation into its anatomical structure. The findings consistently show an increase in the material's heat storage capacity, which each time was attributed to high retention of the PCM within the wood. The degree of improvement is closely related to the anatomical properties of the impregnated wood. By increasing the number of empty spaces, more PCM can be impregnated into wood, resulting in improved dimensional stability. It has been shown that incorporating a PCM into wood does not impact its mechanical properties. The impregnation of PCM in wood used in construction provides a compelling solution due to its potential for improved thermal properties compared to untreated wood. This approach offers the opportunity to enhance the thermal mass of buildings and effectively regulate temperature fluctuations inside residential environments. However, a significant downside is that PCM leaks can occur during the phase change process. To address this issue, researchers often rely on a coating to encase the PCM and prevent any potential leakage. Other methodologies described below have been developed to avoid it. Table 1 summarizes the research results described above.

## Impregnation of Microencapsulated PCM in Wood

One way to prevent leakage of material during heat storage is by using microencapsulated phase change materials (MPCMs). These capsules typically range in size from one to hundreds of micrometers and resemble a white powder in appearance. Lin *et al.* (2020) developed a heat storage wood using PEG-800 as PCM. The authors used graphene aerogel to microencapsulate the PCM and prevent leakage. The resulting composites showed a latent heat of fusion of 11.8 J/g. This is a low value compared to those obtained in the studies described above. The integration of graphene aerogel increased the thermal conductivity of wood by 274%. Thermogravimetric analysis demonstrated exceptional thermal stability within the composite, starting the weight loss above 230 °C.

In a recent study, Mathis *et al.* (2018b) impregnated red oak and sugar maple woods with MPCM to evaluate its potential as a component in the development of novel wood flooring with high thermal properties. The total heat storage in red oak samples was 7.6 J/g, signifying a 77% enhancement in thermal mass compared to non-treated wood. The impregnation of sugar maple wood with PCM proved to be challenging Therefore, its increase in heat storage capacity (quantity of heat that can be absorbed and retained by the material considering both, sensible heat linked with temperature variations, and latent heat linked with phase changes) was negligible.

Similarly, Wang *et al.* (2020) used a MPCM emulsion to impregnate delignified balsa wood, aiming to investigate its potential for temperature regulation for building energy preservation. The latent heat of the resulting composite was 44.3 J/g with a phase change temperature of 27.2 °C. Throughout the heating or cooling process, natural wood did not exhibit endothermic and exothermic peaks. These were visible after the MPCM was incorporated, indicating that the energy storage capacity comes from the MPCM. The addition of graphene into the composite increased its thermal conductivity by about 773%, showing a value of 0.873 W/m K.

## Application of Macroencapsulated PCM in Wood Construction

To avoid leaks of PCM during phase change, some researchers used macroencapsulation. Mathis *et al.* (2019) developed wooden panels using an etched medium density fiberboard (MDF) embedded with plastic pouches laden with bio-based PCMs. A high-density fiberboard (HDF) was employed as an upper layer to include the macroencapsulated PCM within the wooden panel's structure. The phase change temperature of the PCM was 22.2 °C, and the highest total heat storage of the panels was 57.1 J/g. Thermal cycling tests revealed thermal reliability in all cases. This innovative panel offers the ability to store thermal energy and could also be used as a decorative element in building applications. A full-scale experiment using these panels was carried out by Mathis *et al.* (2018a) in a cold climate. The thermal behavior of the panels was evaluated in a light-frame test hut and was compared with a second hut equipped with a standard envelope including an interior gypsum board. The indoor temperature and heating energy consumption were monitored. A decrease in energy consumption for heating was attained during the cold season. However, the reduction was not as significant during the colder months because of the higher energy consumption necessary to uphold the desired temperature within the experimental hut. However, as the outside temperature increased in the spring, there was higher availability of radiative heat from the sun. Therefore, the heating consumption decreased between 8.7% and 41% as a function of the outside conditions, in the hut including macroencapsulated PCMs panels. During the summer, the results indicated that the panels including PCMs were capable of partially mitigating the problem of excessive heat buildup in the hut.

In a similar study, Sonnick *et al.* (2018) used a eutectic salt hydrate mixture inside sealed plastic pouches that were placed in different locations in a prefabricated wooden house. The temperature was monitored over a 10-month period under real environmental conditions. The results showed a high reduction in temperature fluctuations as a result of a high storage capacity of the PCM. A macroencapsulated PCM (M-PCM) using n-octadecane in nylon packing bags was used by Chang *et al.* (2017) to analyze the thermal behavior of wood-frame walls. The phase change temperature of the PCM was 29.8 °C and the latent heat of fusion was 256.5 J/g. These values are higher than those previously reported in other studies, indicating a high heat storage capacity. The M-PCM was used in hot and humid weather conditions prevailing in the summer. The results showed that M-PCM improved the performance of the wood-frame structures by enhancing the comfort of the indoor environment. Using simulations, Salgado (2016) showed that the incorporation of a commercial macroencapsulated PCM in the structure of a wooden house could improve its thermal inertia, thereby reducing thermal discomfort indoors. Simulations were also performed considering the PCM in different positions within the walls and ceilings. Different climatic conditions were considered. The simulation results showed that up to 35.2% more hours within the comfort zone were achieved when incorporating the PCM within the house envelope.

Using macroencapsulation can be a great solution to prevent PCM leaks. However, if the bags filled with PCM are used in the walls, ceilings, or floors of wooden houses, they can accidentally break due to a nail or screw puncture during construction. To avoid this, it is important to take adequate measures to protect the macroencapsulated PCM. Table 2 summarizes some relevant aspects of the studies described above.

**Table 2.** Summary of Studies Carried out with Macroencapsulated PCM in Wood

| PCM | Support Material | Method Used | Fusion Temperature of Composite (°C) | References |
|---|---|---|---|---|
| Lauric and capric acid | Wood-based panel (HDF-MDF) | Macroencapsulation | 20 | (Mathis *et al*. 2019) |
| PT23 | Wood-based panel (HDF-MDF) | Macroencapsulation | 23 | (Mathis *et al*. 2018a) |
| Eutectic salt hydrate mixture | Prefabricated wooden house | Macroencapsulation | 21 | (Sonnick *et al*. 2018) |
| n-Octadecane | Wood structures | Macroencapsulation | 29 | (Chang *et al*. 2017) |
| BioPCM | Walls, ceilings in wooden house | Dynamic thermal simulation | 21-27 | (Salgado R. 2016) |

## Wood / Shape Stabilized PCM Composites

Leakage of PCMs is a common issue. This section discusses studies that aim to develop wood/PCM composites that do not require any coatings to prevent leakage after impregnation.

Ma *et al.* (2019) fabricated a shape-stabilized PCM designed for thermal storage by using a capric-palmitic eutectic acid (CA-PA) mixture as an impregnant. Firstly, the wood slices underwent delignification using a solution of NaOH and $Na_2SO_3$. Following this, the PCM mixture was impregnated into the wood slices utilizing a vacuum-assisted technique. Non-delignified wood samples were also impregnated. Scanning electron microscopy (SEM) results revealed that the pores of delignified wood were filled with PCM. An FTIR analysis was used to determine the type of bond formed between the wood samples and the PCM. The results demonstrated the absence of chemical bond formation among the constituents of the composites, which indicates that only physical bonding occurred. The latent heat of fusion reached was 94.4 J/g, reflecting a 27.9% increase in comparison to lignified samples. The phase change temperature was 23.4 °C. In addition, the shape-stabilized composite exhibited superior thermal stability and enhanced thermal reliability following 100 thermal cycles in comparison to samples containing lignin.

Similarly, Meng *et al.* (2020) developed a shape-stabilized PCM using balsa wood. The wood samples were treated to remove lignin before being impregnated with PEG as a PCM under vacuum. The encapsulation capacity (proportion of PCM impregnated within the wood) as a function of time was measured. The results showed a high encapsulation capacity of 83.5%, achieving a latent heat of fusion of 134.0 J/g. It was noted that the capability of melted PEG to encapsulate was enhanced subsequent to the elimination of lignin from the wood structure. Moreover, the composite that was produced displayed outstanding thermal and chemical stability during 200 consecutive heating and cooling cycles. There were no substantial modifications in latent heat or phase change temperature fluctuations. Jiang *et al.* (2018) evaluated the heat storage capacity of fatty acid / wood flour (WF) composite as shape-stabilized PCM. The PCMs used were incorporated in the wood flour by a direct impregnation method. The SEM images revealed the successful filling of the porous voids within the wood flour by the PCM, ensuring a leakage-free encapsulation. The results of the leakage test confirmed that the shape-stabilized composite can maintain its form and remain leak-free during heating. The FTIR results indicated the absence of chemical reactions, implying solely physical interactions between the supporting material and fatty acids. Using hexadecanoic acid as PCM, the obtained composite showed a latent heat of fusion of 102.6 J/g. The results obtained from thermal cycling tests demonstrate that the composite had good chemical stability and thermal reliability. In conclusion, the prepared shape-stabilized composite has potential applications in buildings, particularly in the realm of heat storage.

Cheng and Feng (2020) created a shape-stabilized PCM composite employing delignified poplar wood flour and an impregnation method with myristyl alcohol as PCM. Leakage tests showed that the composite maintained its initial solid state without any observable liquid seepage following a 30-minute heating period at 80 °C. The latent heat achieved was 175.5 J/g with an 80% (by weight) PCM content. The resulting composite exhibited excellent shape and thermal stability. Sari *et al.* (2020) developed an environmental friendly composite using a eutectic mixture of capric acid and stearic acid combined with wood fibers. The SEM images suggested that the eutectic PCM had been effectively impregnated into the wood fibers. The composite showed a fusion temperature of 23.4 °C and a measured latent heat of fusion of 92.1 J/g. The heat storage capacity and chemical structure remained stable after 600 heating/cooling cycles. Thermal performance tests demonstrated that the resulting composite can be a thermoregulatory component in roofs, walls, floors, and ceilings of wooden frame buildings.

Liang *et al.* (2019) used vacuum absorption to make a PEG / wood flour composite. The authors employed FTIR to determine the chemical composition and structure of the composite. The results suggested that solely physical interactions occur between PEG and WF. There was no chemical reaction between either component. The latent heat of fusion was 108.6 J/g, and the resulting composite had good thermal reliability and was stable after 100 accelerated thermal cycles. In a similar study, Jiang *et al.* (2020) prepared PEG/WF composites. The PEG used was incorporated in the supporting material by a direct impregnation method. The resulting composite showed a maximum latent heat of fusion of 90.9 J/g and an encapsulated ratio of PEG/WF of 52.8%. To determine the latter, the latent heat of fusion of PEG/WF was divided by the latent heat of fusion of pristine PEG and then multiplied by 100. The fusion temperature of the composite was 36.8 °C. The composite demonstrated a good thermal stability, initiating its decomposition at temperatures exceeding 200 °C. In conclusion, the prepared PEG/WF composite has potential application as building material for heat storage.

Yang *et al.* (2017) impregnated poplar sawdust using PEG to obtain shape-stabilized PCM. The resulting composite showed a high latent heat of fusion of 151.1 J/g and a fusion temperature of 58.1 °C. The poplar sawdust / PEG shape-stabilized composite showed no PEG leakage. The FTIR results revealed the absence of novel peaks, signifying the presence of solely physical interactions between the PEG and the poplar sawdust. Montanari *et al.* (2019) used vacuum impregnation to develop a transparent wood for heat storage (TW-TES). They impregnated delignified silver birch wood with PEG as PCM and used methyl methacrylate as a polymer matrix to trap the PCM and form a shape-stabilized composite. The results showed that TW-TES had a latent heat of 76 J/g and was thermally stable below about 290 °C according to TGA testing. Also, TW-TES showed a 6% increase in optical transmittance after the phase change of the impregnated PCM occurred.

The performances of the compounds described above exhibited a common characteristic: little or no leakage of PCM occurred during the phase change process. In this context, the encapsulation capacity of the PCMs were higher than 80%. A significant amount of PCM into the wood structure results in an improved latent heat of the samples, with values exceeding 80.0 J/g in most of the studies outlined. One prevalent attribute is the similarity of phase change temperatures between the obtained compounds and the original PCM utilized. There was no report on the influence of PCM on mechanical properties. This is mainly because PCM was incorporated in wood flour, sawdust, or small wood particles/fibers. For all the investigations described, the FTIR results indicated that the bonding of PCM with wood was physical without chemical reaction between them. Table 3 summarizes some relevant aspects of the shape-stabilized wood / PCM composites described above.

**Table 3.** Summary of Investigations Carried Out On Shape-Stabilized Wood / PCM Composites

| PCM | Support Material | Method Used | Melting Temperature of Composite (°C) | References |
|---|---|---|---|---|
| Capric-palmitic acid eutectic mixture | Wood slices | Vacuum impregnation | 23 | (Ma *et al*. 2019) |
| Capric-stearic acid eutectic mixture | Wood fibers | Vacuum impregnation | 23 | (Sarı *et al*. 2020) |
| Lauric acid; myristyl acid; hexadecanoic acid and stearic acid | Wood flour | Impregnation | 40, 51, 59 and 53 | (Jiang *et al*. 2018) |
| Myristyl alcohol | Wood flour | Vacuum assisted infiltration | 42 | (Cheng and Feng 2020) |
| Polyethylene glycol | Balsa wood | Vacuum impregnation | 41 | (Meng *et al*. 2020) |
| Polyethylene glycol | Wood flour | Vacuum adsorption method. | Between 44 and 65 | (Liang *et al*. 2019) |
| Polyethylene glycol | Wood flour | Direct impregnation | 37 | (Jiang *et al*. 2020) |
| Polyethylene glycol | Poplar sawdust | Vacuum impregnation | 58 | (Yang *et al*. 2017) |
| Polyethylene glycol | Silver birch wood | Vacuum infiltration | 38 | (Montanari *et al*. 2019) |

## Other Applications of PCM in Wood-based Composite Materials

Wood plastic composites (WPCs) have been available on the market for a while now. There have been some studies conducted to assess the effectiveness of WPCs when incorporating PCMs. For example, Xing *et al.* (2020) developed an innovative composite using polyvinyl chloride (PVC), wood flour, and a capric-palmitic acid (CA-PA) eutectic mixture. According to the findings, WPCs containing a suitable proportion of PCM displayed outstanding mechanical characteristics, making them ideal for use as energy-efficient building materials. However, when the CA-PA eutectic content was high, the samples showed low bending, tensile, and impact strength. A DSC analysis has shown that the composite had a phase change temperature of 22 °C with a latent heat of fusion of 28.2 J/g, which represents an opportunity for heat storage applications. Furthermore, the resulting WPCs exhibited excellent thermal stability according to TGA. They also had good thermal reliability after 500 heating and cooling cycles.

Zhao *et al.* (2022) used a WPC composite as the matrix to incorporate PEG/organic diatomite, a latent heat storage agent. The resulting composite had a latent heat of fusion of 60.4 J/g. After undergoing 500 cycles, the material demonstrated commendable thermal reliability and stability. On the other hand, the PCMs used had an adverse influence on the mechanical properties of the composite, which could be attributed to the weak interface interaction between the PCM and the WPC. Using a similar approach, Guo *et al.* (2016) developed microencapsulated PCMs using *in situ* polymerization and incorporated them in WPC composites through an extrusion process. The material obtained was cut into pellets and oven-dried to remove moisture. Subsequently, the composites were fabricated through the application of controlled conditions in a hot-pressing process involving the dried pellets. The results revealed the successful incorporation of microcapsules into the composite and provided a good heat storage capacity according to DSC analysis. The mechanical tests showed that using microcapsules resulted in a reduction of the bending and tensile properties. Thus, using microencapsulated PCMs in applications where mechanical properties are not important is recommended. On the other hand, the microencapsulated PCM had suitable phase change temperatures: melting at 27 °C and solidification at 11.3 °C.

Using a similar methodology, Jamekhorshid *et al.* (2017) prepared WPCs with heat storage capacity using the compression molding technique. The incorporated PCMs were various types of commercial microcapsules. The results showed that the composites obtained could be used for thermal management in indoor environments. The analysis of the thermal properties indicated that latent heat of fusion was 42.8 J/g. It was observed that the bending properties of WPCs decreased after incorporating the microcapsules. However, the leak test indicated that there were no significant mass losses during phase change. The minimal reported loss may have been due to moisture loss from the composites. Guo *et al.* (2018) prepared heat storage composites using expanded graphite, paraffin as a PCM and wood flour / HDPE WPC as a support matrix. The results showed that the composite had a good heat storage capacity and efficiency for preventing temperature variations. Conversely, the incorporation of the PCM led to a reduction in thermal conductivity. The results indicated a decline in both bending strength and stiffness of the composites following the addition of graphite and the PCM. Wood-plastic composites are designed for situations with high humidity and other adverse conditions that may not be suitable for MDF or particleboard. Incorporating a significant amount of PCM into building elements designed for outdoor use provides improved heat storage capacities. One example is a terrace floor made with WPC, which can store a considerable amount of heat from the sun throughout the daylight hours. At night when temperatures are lower, the heat would be released, thus providing a better thermal sensation to the users.

A different PCM application was reported by Qi *et al.* (2020). They fabricated a hollow wood-based fiberboard with embedded PVC tubes which are subsequently filled with PEG as PCM. The samples were fabricated by hot pressing and their physical and mechanical properties were tested. The results showed an increase in bending strength and stiffness upon the incorporation of hollow PVC tubes into the wood composite. This was attributed to the stiffness and other features of the PVC tubes. There were no significant differences in the internal bond strength. The thermal properties of the composite were simulated. The results showed a better performance than concrete in regulating indoor temperature.

Fernández *et al.* (2020) studied thermal and mechanical properties of plywood panels that had been thermally improved through the incorporation of microencapsulated paraffin wax (MikroCapsPCM28). Three plywood boards with dimensions of 300 by 300 mm were prepared. Of these, one was a control board and the other two had PCM in a proportion of 25% and 30% by mass. The results showed no significant difference between the bending strength and stiffness of the samples with PCM and the control sample. On the other hand, a custom-designed experimental arrangement was employed to assess the influence of the PCM on the thermal performance of the plywood samples. The incorporation of PCM enhanced the thermal mass of the plywood panels by as much as 19%. This study is unique in its use of PCMs in wood-based panels. Currently, there are no previous examples of MDF, OSB, or particleboard incorporating such materials.

## PATENTS RELATED TO THE USE OF PCMS IN WOOD

Researchers have developed processes and new composites using various PCMs in wood, which have been patented. Table 4 presents some of the patents related to the utilization of PCMs in wood.

**Table 4.** Patents Related to the Utilization of Phase Change Materials in Wood

| Patent number | Date | Title |
|---|---|---|
| EP1649221B1 | 07-11-2007 | Wall integrated thermal solar collector with heat storage capacity |
| ES05812787T | 10-03-2007 | Phase change material (PCM) compositions for thermal management |
| US20100294980A1 | 11-25-2010 | Cellulosic fibers having enhanced reversible thermal properties and methods of forming thereof |
| TWI376438B | 11-11-2012 | Cellulosic fibers having enhanced reversible thermal properties and methods of forming thereof and fabrics |
| CN102677860 | 08-20-2014 | Phase change energy storage temperature regulation energy-saving floor |
| JP2015134931A | 07-27-2015 | Thermal regulating building materials and other construction components containing polymeric phase change materials |
| CN106589519 | 04-26-2017 | Phase-change heat-storage wood-plastic composite and preparation method thereof |
| CN106625930 | 02-01-2019 | Phase-change energy storage heat-insulation solid wood and manufacturing method thereof |
| CN109305782 | 02-05-2019 | Energy storage type wooden enhanced inorganic wall body composite material and preparation method thereof |
| CN109825254 | 05-31-2019 | Polyethylene glycol wood powder composite phase change material (PCM) and preparation method and applications thereof |
| CN110055036 | 07-26-2019 | Preparation method of hydrated salt-porous wood compound phase change energy storage materials |
| US20190249904A1 | 08-15-2019 | Eco smart panels for energy savings |
| CN110512794 | 11-29-2019 | Phase change energy storage plate and manufacturing method thereof |

## CHALLENGES AND OPPORTUNITIES IN WOOD / PCM COMPOSITES

Considering the extensive research on the use of PCM in materials such as concrete, plaster, brick, *etc*., published research using wood as a support material is relatively scarce. This provides opportunities to study how the different types of PCMs can be incorporated into wood. Wood anatomical features play a significant role in selecting the type of PCM and the method of incorporation to be used. Another important aspect to consider is the desired phase change temperature. This will mainly be determined by the climatic conditions of the location where the material will be used.

However, there appears to have been no research regarding the integration of PCMs into wood-based composite panels such as OSB, fiberboard, or particleboard. Incorporating PCM properties into wood-based composites presents an opportunity to enhance their thermal properties for use in building envelopes, interior wall coverings, ceilings, floors, window frames, and doors. These features could help to regulate indoor temperature and reduce energy consumption.

## CONCLUSIONS

This paper reviewed studies addressing the use of phase change materials (PCMs) in wood and wood-based composites. There are various application methods, and depending on the type of PCM, there are variations in performance:

1. First, studies on direct impregnation in wood were introduced. Morphological analysis, thermal stability, heat storage properties, among other types of characterization were analyzed and compared. The impregnation processes that were preceded by wood delignification showed a greater capacity for PCM incorporation. This translates into higher heat storage capacity.
2. Then, the use of macroencapsulated PCM in the interior of wooden structures and shape-stabilized composites developed to prevent the loss of PCMs during the phase change process were discussed. The problem of leakage during phase change of conventional PCMs remains a major concern, and research efforts should focus on controlling it.
3. Finally, there exists the potential to integrate PCMs into existing market-available materials, including wood-plastic composites. In all cases, published results indicate a positive impact on the thermal behavior of the material.
4. Currently, there are many research opportunities in this area, including the use of different wood species and the development of novel wood-based panels with better heat storage capacities. Future challenges include the simplification of the incorporation methods and the reduction of the production cost of these composites.

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