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HỘI THẢO KHOA HỌC QUỐC GIA
Quản lý, khai thác và sử dụng hiệu quả bền vững tài nguyên trong nền kinh tế hội nhập

2025



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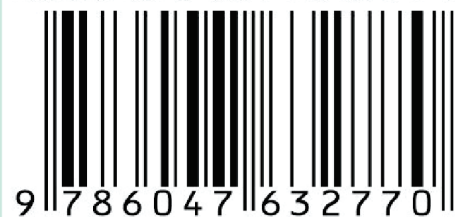


ĐẠI HỌC KINH TẾ QUỐC DÂN

HỘI THẢO KHOA HỌC QUỐC GIA

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Tài nguyên trong nền kinh tế hội nhập

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Wood - Based Phase Change Materials: A Sustainable Solution for Energy Efficiency and Resource Management

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ABSTRACT

Phase change materials (PCMs) are emerging as effective thermal energy storage media for improving energy efficiency in buildings and other systems. Wood-based PCMs, which use wood or wood-derived materials as support matrices for latent heat storage, offer a renewable and sustainable approach to thermal management. Wood-based PCMs show applications in moderating indoor temperatures and reducing energy consumption, highlighting environmental benefits such as a lower carbon footprint and the utilization of renewable biomass. Production techniques include direct impregnation, encapsulation, and the formation of shape-stabilized composites, along with recent advances that enhance thermal conductivity and material strength. Key challenges, such as PCM leakage, flammability, and cost, are analyzed alongside opportunities for innovation and large-scale implementation. The current state and potential of wood-based PCMs in Vietnam's context are evaluated, given the country's abundant wood resources and its integration into the global sustainable economy. Overall, wood-based PCMs represent a promising convergence of bio-based materials and energy technology, contributing to sustainable resource management and energy-efficient design.

Keywords: Phase Change Material, PCM/Wood, Composite, Thermal Energy Storage (TES)

1. Introduction

Rising global energy demand and climate change concerns have spurred interest in improving energy efficiency, particularly in the building sector which accounts for about 40% of total energy consumption (Solgi E., 2019). Thermal energy storage using phase change materials (PCMs) is a well-established strategy to reduce energy use by storing excess heat and releasing it when needed, thus flattening demand peaks (Yang et al. 2020). PCMs absorb and release latent heat during phase transitions (typically solid–liquid), allowing thermal energy to be stored at nearly constant temperature (Vennapusa et al. 2020). Common PCMs include organic materials (e.g. paraffin waxes and fatty acids) and inorganic salts; organic PCMs are often favored for building applications due to their favorable cycling stability, non-corrosiveness, and tunable phase change temperatures (Hanif, F et al., 2023). However, many PCMs suffer from drawbacks such as low thermal conductivity, risk of leakage in liquid state, and flammability.

To address these issues and improve sustainability, recent research has focused on wood-based PCMs, which use natural wood or wood-derived structures as supporting matrices for the PCM. Wood is a renewable, bio-based material with a porous structure that can host PCMs (Nazari M. et al., 2020). Integrating PCMs into wood produces composite materials that combine the heat storage capacity of PCMs with the structural and insulating properties of wood (Lachheb M., et al, 2017). This approach yields bio-based thermal energy storage materials that align with sustainable resource management goals. Wood-based PCMs can be considered a form of shape-stabilized PCM, where the wood scaffold physically contains the PCM and prevents it from flowing out during melting (Wan et al. 2019). By leveraging wood's hierarchical porosity and mechanical strength, such composites can mitigate PCM leakage and even improve mechanical robustness of the overall material (Cheng et al, 2020), (Yang, 2025). Crucially, using wood (especially wood waste or byproducts) as a PCM carrier adds value to biomass resources and reduces reliance on petroleum-based encapsulation materials, enhancing the sustainability profile of thermal storage systems.

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Wood-based PCMs are especially relevant for building applications aimed at passive thermal regulation and energy saving (Mathis D., 2019). In tropical and subtropical climates like Vietnam's, buildings face significant cooling loads; materials that moderate indoor temperatures can cut air-conditioning demand and improve comfort. Vietnam is a major processor and exporter of wood products, ranking among the world's top five wood product exporters and the largest exporter of woodchips (Borer, 2024). Over 30 million cubic meters of wood are processed annually into furniture, boards, wood chips, pellets and other products. This generates substantial quantities of sawdust, shavings and other wood waste – indeed Vietnam was the 4th largest exporter of wood waste and pellets in 2021. Utilizing wood waste to produce wood-based PCM composites represents a circular economy opportunity to turn industrial byproducts into high-value, energy-saving materials. This review, written in a simple scientific style, surveys recent progress in wood-based PCMs, including their applications and environmental benefits, fabrication techniques and research advances, challenges and opportunities, and their role in a sustainably integrated economy with a focus on Vietnam.

2. Applications and Environmental Benefits of Wood-Based PCMs

Building thermal management is the foremost application of wood-based PCMs. By incorporating PCMs into building components (walls, floors, ceilings, etc.), the thermal mass of the structure is increased, dampening indoor temperature swings and reducing heating/cooling energy needs (Hu J., 2019). Wood itself is a common building material, so developing wood-based composites with latent heat storage can lead to “smart” construction materials. In one experiment, macro-encapsulated PCM panels (paraffin-filled pouches inside wood-based boards) installed in a test hut in a cold climate cut heating energy consumption by up to ~9–41% during milder cold days (Rodríguez, G, 2023). During hot summer conditions, PCM-enhanced wood walls were able to mitigate indoor overheating, keeping interior temperatures more comfortable compared to ordinary walls. Another study in a tropical context (South Korea) found that incorporating macro-packed PCMs in wooden framed walls (PCM melting point ~29.8 °C) improved hygrothermal performance and indoor comfort in summer, thanks to the PCM absorbing excess heat during the day (Chang, 2017). These results demonstrate the benefit of wood/PCM systems in reducing HVAC loads and enhancing occupant comfort.

Wood-based PCMs can be integrated into prefabricated building elements. Researchers have developed wood-PCM composite boards and evaluated them in full-scale rooms. By installing PCM-wood panels in a test building, indoor temperature fluctuations were significantly reduced, and more hours fell within thermal comfort range without active HVAC, compared to a reference building (Chang, 2017). Such passive regulation is particularly valuable in climates with high diurnal temperature variation or intermittent energy access. In Vietnam and other ASEAN countries, peak electricity demand for cooling occurs during hot daytime hours. Wood-based PCM building materials could shift cooling loads to off-peak times by absorbing heat in daytime and releasing it at night, complementing daylighting and natural ventilation strategies.

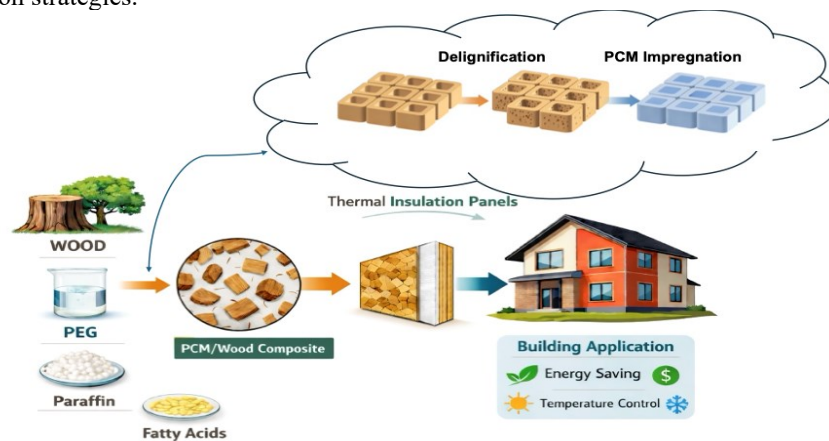


Figure 1. Building application of PCM/Wood

From an environmental sustainability perspective, wood-based PCMs offer multiple advantages. First, they utilize renewable biomass instead of solely synthetic materials. Wood is a carbon-sequestering resource; using wood in long-lived composites keeps that carbon stored rather than quickly released. If bio-based PCMs (such as plant-derived fatty acids) are used instead of paraffin, the entire system can be

fossil-free and even biodegradable. Second, wood-based PCMs can recycle wood industry waste. Sawdust, wood shavings, and off-cuts can be processed into wood flour or porous panels that serve as PCM hosts (Liang, 2019). Vietnam produces millions of tons of wood waste annually and is a leading exporter of woodchips and pellets; diverting a portion of this biomass into PCM composites could reduce waste exports and promote domestic high-value manufacturing.

Another benefit is improved material lifespan and insulation performance. Impregnating wood with PCM often renders it more dimensionally stable and moisture-resistant. A recent study on spruce wood impregnated with commercial PCMs found that after treatment, the wood's water absorption dropped by 28% and its swelling (tangential) was reduced by 75% (Can, 2023). The PCM-filled wood became more hydrophobic, which also made it resistant to wood-decay fungi. This implies that PCM impregnation can act like a protective treatment, potentially reducing the need for separate chemical preservatives. Lower moisture uptake also means better insulation (dry wood is a better insulator), compounding the energy-saving effect.

Lastly, energy savings from wood-based PCMs translate to environmental gains by cutting fossil fuel use and greenhouse gas emissions. By smoothing out indoor temperatures, these materials reduce reliance on heating with coal/gas or cooling with electricity (often generated from fossil fuels). One modeling study showed that adding PCM into wooden building envelopes increased the hours of thermal comfort by over 35% and significantly decreased HVAC energy usage. Over a building's life, such efficiency improvements can yield substantial carbon emissions reductions. Applications of wood-based PCMs in buildings and other domains offer dual benefits: direct energy conservation and improved resource sustainability. They make use of natural, renewable components while improving thermal regulation, aligning well with green building principles and the circular economy.

3. Production Techniques and Recent Advances

Creating wood-based PCM composites involves infusing or encapsulating PCMs within the wood's porous structure. Several production techniques have been developed:

Direct Impregnation: In this simplest method, wood (or a wood-based material) is soaked in liquid PCM, often under vacuum or pressure to enhance penetration into pores. The PCM then solidifies inside the wood's cell cavities. Direct impregnation has been demonstrated with various wood species and PCMs. Barreneche et al. vacuum-impregnated paraffin into black alder wood, achieving ~20.6 J/g latent heat at ~30% PCM weight (Barreneche et al. 2017). Li et al. (2016) impregnated Douglas-fir with polyethylene glycol (PEG) and obtained a higher latent heat (~73.6 J/g) and stable performance over 400 thermal cycles. Vacuum or pressure impregnation is generally needed because wood's pore structure contains air and bound moisture that hinder PCM uptake; by applying vacuum, the air is removed and PCM can fully infiltrate. Using this approach, researchers have reported PCM loadings up to 60–80 wt% in wood. Nam et al. impregnated balsa wood with n-octadecane and reached a latent heat of ~49.7 J/g at significant PCM loading, while cork (which is more porous) reached 131 J/g (Nam et al, 2022). A key finding is that higher PCM content in the wood yields higher composite enthalpy, as expected. However, a major challenge of direct impregnation is PCM leakage: when the PCM melts, it can seep out of the wood unless contained by some means.

Microencapsulation and Impregnation: One solution to leakage is to microencapsulate the PCM first – i.e. enclose PCM droplets in tiny shells (made of polymers or inorganic materials) – then impregnate these microcapsules into the wood. The microcapsules act like plug-fit “fillers” in the wood pores, retaining the PCM even when it liquefies. Borreguero et al, and others have demonstrated this approach, successfully loading wood with microencapsulated PCMs without seepage (Barreneche et al. 2017). Incorporating commercial micro-PCM into balsa wood: one study impregnated delignified balsa with 6.5 μm microcapsules containing PCM and added graphene nano-powder to improve thermal conductivity. The result was a “phase change energy storage wood” composite that showed no liquid leakage during heating and had enhanced heat transfer due to the conductive graphene network (Hanif, 2023). The microencapsulation route, however, increases processing complexity and cost, and the total PCM content is limited by the capsule walls and the wood's capacity.

Macro-encapsulation in Wood Structures: Another method is to embed larger PCM containers within wood building elements. Wooden panels with PCM pouches have been made by sandwiching plastic foil packets of bio-based PCM between layers of fiberboard. Mathis et al. created such panels using an etched MDF to hold PCM pouches and sealed them with a high-density fiber-board layer (Mathis D., 2019). The panels, with a PCM melting at ~22 °C and ~57 J/g heat storage, were structurally sound and decoratively usable. Similarly, Chang et al. inserted nylon bags of octadecane PCM into wood-frame wall cavities; the PCM (melting at ~29.8 °C, latent heat ~256.5 J/g) significantly improved summer comfort in a hot, humid

climate by absorbing heat, thus keeping indoor peak temperatures lower (Chang, 2017). Macro-encapsulation prevents direct contact between PCM and wood, thus eliminating leakage issues during phase change. However, it introduces concerns about package durability.

Shape-Stabilized Wood/PCM Composites: A major advance in recent years is the development of shape-stabilized PCMs using wood as a scaffold. In this approach, the wood itself (or wood-derived material like fibers or charcoal) holds the PCM via capillary and surface forces, eliminating the need for any encapsulating shell. To maximize PCM uptake, chemical or thermal modifications of the wood are often employed. Delignification is one effective treatment: removing lignin (and partially hemicellulose) from wood opens up the structure, leaving behind a cellulose-rich porous network that can imbibe large amounts of PCM. Carbonized wood (i.e. wood pyrolyzed to form a porous carbon skeleton) is another support that can hold PCM effectively and also boost thermal conductivity. Cheng & Feng used delignified poplar wood flour, then carbonized it to create a high-surface-area carbon matrix which was impregnated with alcohol PCM (Cheng, 2020). The composite contained an impressive ~80 wt% PCM and showed no leakage even when heated 30 minutes at 80 °C (well above the melt point). It had a very high latent heat of 175.5 J/g thanks to the high PCM loading. The PCM is held by physical confinement within pores and by surface tension, meaning the wood acts as an inert structural host.

Recent advances in wood-based PCM research have focused on improving performance metrics such as thermal conductivity, mechanical strength, and multifunctionality:

Thermal Conductivity Enhancement: Both wood and organic PCMs have low thermal conductivity (around 0.1–0.2 W/m·K for wood, and even lower for many PCMs), which can slow the charging and discharging of heat. Researchers have introduced conductive additives or used carbonized wood matrices. Carbonized wood can greatly increase conductivity, a carbonized wood/PCM composite had 0.669 W/m·K, over 114% higher than the PCM alone (Hanif, 2023). Adding graphene powder into a PCM-impregnated wood composite increased its thermal conductivity by 773%, reaching 0.873 W/m·K (Rodríguez, G., 2023). Similarly, incorporation of metallic or ceramic nanoparticles (e.g. Al₂O₃, SiC nanowires) has been explored. Silicon carbide nanowires added to a pine wood/paraffin composite, which not only enhanced thermal conductivity but also helped anchor the PCM to prevent leakage.

Mechanical and Structural Improvements: A remarkable benefit of using a wood scaffold is that the composite can inherit wood's mechanical strength. Pure PCMs are often waxes or salts that have little structural integrity (brittle when solid, liquid when melted). In contrast, wood is a load-bearing material. By impregnating strong yet flexible wood, researchers achieved mechanically robust PCM composites. The inherent “self-skeleton” of wood provides mechanical support to the soft PCM, meaning wood-based PCMs can double as construction materials, unlike most standalone PCMs. Furthermore, some researchers have explored transparent wood PCMs where a polymer (like epoxy or PMMA) is introduced with the PCM to maintain optical clarity of delignified wood. The composite stored ~76 J/g latent heat and interestingly became more translucent upon PCM melting (optical transmittance increased by ~6%) (Rodríguez, G., 2023). Such materials could be used as innovative window panels that store solar heat while allowing light, contributing both daylighting and passive heating in buildings.

Photothermal and Multi-Functional PCMs: A cutting-edge area is photothermal wood-based PCMs, which not only store thermal energy but also harvest solar energy. By carbonizing wood or adding light-absorbing additives, the composite can act as a solar thermal collector. Carbonized wood is black and absorbs sunlight effectively, converting it to heat. A carbonized wood/paraffin composite achieved a high photothermal conversion efficiency (~90%), heating up significantly more under simulated sunlight than a non-carbonized (delignified) wood/PCM sample (Hanif, 2023). Such innovations are making wood-based PCMs safer and more practical for real-world use.

In summary, production of wood-based PCMs has evolved from simple impregnation to advanced engineered composites. Researchers are now able to fine-tune the wood structure (through chemical treatment, carbonization, densification) and introduce complementary materials (polymers, nanoparticles) to create composites that not only store heat reliably but also overcome many inherent limitations of PCMs. These advances pave the way for wood-based PCMs with high energy density, fast response, structural function, and safety features – all using economical and sustainable materials and processes.

4. Challenges and Opportunities in Using Wood-Based PCMs

Despite the promise of wood-based phase change materials, there are several challenges

Leakage and Durability: PCM leakage during phase transitions is the most commonly cited issue. If the PCM is not completely retained, it can leak out of the wood pores upon melting, causing loss of functionality and potentially damaging surrounding materials. Over tens of thousands of cycles or many years of service, small amounts of PCM might migrate or evaporate. The good news is that many wood-

based PCMs have demonstrated excellent cycling stability in research settings – e.g. stable performance over 100, 200, or even 600 thermal cycles has been reported with negligible loss of latent heat (Rodríguez, G., 2023). This indicates that with proper design, durability is achievable.

Flammability: Both wood and typical organic PCMs (paraffins, fatty acids) are combustible, raising fire safety concerns. Possible approaches include using inherently flame-resistant PCMs (e.g. salt hydrates, but those come with other issues) or treating the composite with flame retardant chemicals (phosphates, borates, etc.). One promising result came from the earlier mentioned PCM composite aerogel: by incorporating a flame-retardant polymer matrix, the composite's flammability was dramatically reduced (over 70% reduction in heat release rate) while maintaining high energy storage (Qiu, 2024). Carbonizing the wood support also naturally reduces flammability. Future research will likely integrate flame retardant strategies (nano-clays, intumescent coatings, etc.) to ensure wood-based PCMs meet fire safety standards for construction.

Thermal Conductivity vs. Insulation: There is an interesting trade-off regarding wood's insulating nature. On one hand, low thermal conductivity is useful for insulation (it slows heat flow, maintaining comfortable interiors). On the other hand, for the PCM to quickly absorb or release heat, higher conductivity is desired. Wood-based PCMs thus need a balance: enough conductivity to charge/discharge the PCM in a timely manner, but not so high that it defeats the purpose of smoothing temperature fluctuations. Many composites incorporate conductive additives to boost heat transfer (as discussed, graphene, carbon fibers, etc.) (Hanif, 2023). These must be optimized so that the effective thermal response of the material matches the application. Conversely, if it conducts too well, heat might leak undesirably. So, design considerations like PCM melting point, composite thermal conductivity, and placement in the building envelope all have to be tuned together.

Cost and Scalability: Replacing or retrofitting standard building materials with PCM-enhanced versions must be cost-effective to gain market acceptance. Presently, some fabrication processes for wood-based PCMs are relatively complex or laboratory-scale. Scaling up production while keeping costs reasonable is a challenge. The raw materials themselves (wood waste, paraffin or fatty acids) are not very expensive, but processing costs could be. It's also worth noting that macro-encapsulation approaches can leverage existing panel manufacturing – embedding PCM packets in prefab panels is not unlike making insulated panels, so it could be integrated into production lines relatively easily (Rodríguez, G., 2023). Overall, demonstrating a clear cost-benefit (energy savings paying back the material cost) will be key. This likely depends on energy prices and regulatory support (or carbon pricing) that value the efficiency gains.

Opportunities: On the positive side, the challenges above are being actively addressed, and they open new research and business opportunities. Given the extensive research on PCM incorporation in materials like concrete, gypsum, etc., wood remains comparatively under-explored, so breakthroughs in wood-based PCMs could quickly gain attention (Rodríguez, G., 2023). One opportunity is tailoring wood species and form for PCM composites. Fast-growing species or plantation timber (like acacia, rubberwood, or bamboo) could be tested for PCM composites, potentially adding value to those resources. Vietnam has large acacia plantations primarily harvested for chips, if even a portion of that wood could be diverted to PCM composite products, it might yield higher economic returns while supporting the push to extend harvest cycles for more valuable uses (Borer D., 2024). There is also an opportunity in the retrofitting market: thin wood-PCM sheets or plasters that can be applied onto existing walls or ceilings of buildings to improve thermal inertia. These could be appealing in heritage buildings or homes where invasive retrofits are difficult.

In summary, while challenges such as leakage, flammability, and cost need continued attention, they are being progressively mitigated through material science innovations. The inherent benefits of wood-based PCMs – renewable content, dual-function as structure and storage, and synergy with existing wood industries – provide strong motivation to surmount these hurdles. With supportive policies and further R&D, the opportunities to commercialize and deploy wood-based PCMs in buildings and other sectors are significant and timely.

5. Wood-Based PCMs in an Integrated Economy: Sustainability in Production and Consumption

Vietnam's economy is deeply integrated into global trade, being a major exporter of wood products, textiles, electronics, etc. (Borer, 2024).. However, much of its wood export volume is in lower-value products like chips and pellets, as noted earlier (over \$1.7 billion in woodchip exports). Instead of simply selling sawdust or small-diameter plantation wood as pulp or fuel, Vietnam could process this biomass into PCM-infused building materials or thermal storage components. These advanced materials could then be used domestically to improve energy efficiency (reducing import needs for energy) or exported to meet growing international demand for sustainable construction solutions.

In terms of sustainable production, wood-based PCMs tick several boxes. They promote the use of certified, sustainably managed wood – since buyers of eco-friendly building materials will likely prefer products made from wood that is harvested legally and replanted. Producing “green” PCM materials could further incentivize sustainable forestry practices. Moreover, manufacturing wood-PCM composites could create jobs in rural areas (where wood processing is common) and utilize existing facilities (kilns, impregnation plants) with some retooling, aiding a just transition for workers into the green economy. By coupling local biomass resources with advanced material tech, countries like Vietnam can reduce reliance on imported materials (such as synthetic insulation or imported PCMs) and build local expertise in clean technology.

On the consumption side, integrating wood-based PCMs in buildings contributes to sustainable consumption by lowering energy usage. In a rapidly developing country, new construction can leapfrog by using passive cooling/heating measures, thereby avoiding locking in high energy demand. In the commercial sector, companies (especially multinational manufacturers in Vietnam) are increasingly pursuing energy savings and might adopt such materials to meet corporate sustainability targets (Net-Zero, 2023).

Sustainability in production also encompasses the end-of-life scenario. Wood-based PCMs, if made with biodegradable PCMs (like bio-waxes or fatty acids), could be designed to be largely recyclable or compostable at end of service. Traditional PCM systems (like a plastic-encapsulated PCM panel) might end up as mixed waste that is hard to recycle. In contrast, a wood-based PCM panel theoretically could be recycled by separating any residual PCM (some of which could even be reclaimed) and using the wood for particleboard or simply bio disposing it.

Policy support will greatly influence opportunities here. If building codes start recognizing or requiring passive thermal energy storage, or if green building certification gives credit for bio-based materials and energy savings, it would accelerate adoption. Vietnam’s government, under its sustainable development strategies, could incentivize pilot projects demonstrating wood-based PCMs in public buildings or export goods. International collaboration, perhaps with research institutions from countries experienced in PCMs (Europe, China, etc.), can help transfer knowledge and adapt technologies to local wood species and climate needs.

Conclusion

Wood-based phase change materials represent a compelling intersection of renewable materials and energy efficiency technology. From direct impregnation of paraffin into timber, to advanced shape-stabilized composites with delignified or carbonized wood, various fabrication techniques have been developed to maximize latent heat capacity while minimizing issues like leakage. Several challenges remain, including ensuring long-term stability (both thermally and mechanically), meeting fire safety standards, and scaling up manufacturing economically.

The case of Vietnam illustrates the attractive sustainability and economic aspects of wood-based PCMs. By harnessing abundant wood resources and industrial byproducts, Vietnam and countries alike can produce home-grown energy-efficient materials. In a world increasingly concerned with sustainable resource management, wood-based PCMs exemplify the kind of circular. They enable storing renewable energy in a renewable material, essentially marrying the concept of energy storage with the principles of sustainable forestry.

In conclusion, wood-based PCMs are a promising and pragmatic approach to enhance energy efficiency in the built environment while promoting the use of sustainable materials.

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