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Investigation of Thermal Conductivity and Energy Storage Performance of Bio-Based Phase Change Materials for Sustainable Building Applications

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Abstract--- With the increased requirement for energy efficient buildings, it has become essential to develop sustainable phase change materials for reducing heating and cooling needs and enhancing indoor thermal comfort conditions. The comparative analysis of renewable phase change material formulations based on thermal characterization and energy storage capability evaluation is what makes it distinctive. The process entails choosing bio-based materials, creating PCMs, and assessing their thermophysical characteristics using TGA, DSC, thermal conductivity measurements, and repeated heating-cooling testing. In terms of melting temperature, latent heat, thermal conductivity, thermal stability, and energy storage capacity, three bio-based formulations are compared. The study and discourse focus on the effect of thermal conductivity enhancement on the performance of charging and discharging, along with the compatibility of the various materials for incorporation into the building envelope. An ideal bio-based composite would have thermal conductivity of 0.42 W/m.K., latent heat storage of 165 kJ/kg, and energy storage efficiency of 88%, according to one sample assessment. The findings demonstrate that well-designed bio-based PCMs may provide temperature control and stabilization within buildings, which reduces energy consumption.

Keywords--- Bio-based Phase Change Materials, Thermal Conductivity, Latent Heat Storage, Thermal Energy Storage, Sustainable Buildings, Thermal Stability, Heat Transfer, Energy Efficiency.

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I. Introduction

Buildings have a significant share of the total world energy usage through the energy required for heating, ventilation, air conditioning, and lighting purposes. There has been a growing concern about climate change, energy prices, and environmental sustainability; hence, scientists are trying to explore new materials that will enhance the energy efficiency of buildings. The use of thermal energy storage techniques offers an efficient solution for controlling temperature variations as well as cutting down on the need for conventional heating and cooling systems (Nalla et al., 2025; Li et al., 2024; Wang et al., 2022). Phase change materials (PCMs) are one of the energy storage solutions that have received much focus due to their capacity to store energy during phase changes. Because they are renewable and can be obtained from biological sources such vegetable oils, fatty acids, and agricultural wastes, bio-based PCMs are an additional choice. While maintaining their capacity to store heat, the prospective application of bio-based PCMs in building materials creates opportunities to improve environmental sustainability (Öztürk et al., 2024; Naresh et al., 2022; Palanti et al., 2022). However, important characteristics like thermal conductivity, melting point, latent heat capacity, thermal stability, and compatibility with building materials are necessary for the application of bio-based PCMs (Zhao et al., 2022). Thermal conductivity and relatively low melting points are some of the limitations of bio-based PCMs (Nazari et al., 2020; Sawadogo et al., 2022). Moreover, leakage when they melt, phase separation, oxidation and thermal cycling may impair the performance of these materials. Thus, finding ways of enhancing the thermal conductivity and developing appropriate composites is essential.

For sustainable building applications, the study investigates the thermal conductivity and energy storage potential of bio-based PCMs (Manar et al., 2025). The different formulations will be characterized thermally

and analyzed in terms of performance. The study looks at selecting the right melting point, improving heat transfer capabilities and having sufficient latent heat storage capacity.

This study will endeavour to create a link between the three variables mentioned above. The results of the study should help in the creation of sustainable thermal storage materials that can facilitate better temperature regulation indoors and lower cooling and heating needs, hence creating more energy-efficient buildings.

Problem Definition

Traditional building materials have little capability for storing and releasing heat, leading to variations in room temperatures and greater need for heating and cooling systems. While Phase Change Materials are good at storing thermal energy, many conventional formulas contain non-renewable substances and cause environmental hazards. In this case, bio-based PCMs are more sustainable, but the low thermal conductivity can limit heat conduction and reduce charge and discharge rates. Other problems consist of possible leakage upon melting, thermal decomposition, irregular phase transitions, as well as low thermal stability. Moreover, it is necessary to examine the correlation between enhancing thermal conductivity and latent heat storage efficiency. The problem is that without proper material optimization, the bio-based PCMs will be incapable of regulating thermal performance for construction. That is why this study is aimed at investigating renewable PCM formulas, thermophysical properties and finding suitable material composition.

Outline of the Study

The paper comprises various interconnected sections, which are concerned with thermal and energy storage properties of biopolymer based PCMs. Section 1 deals with the background of the research, the problem statement, and the objectives of the research. Section 2 is devoted to reviewing developments in biopolymer-based PCMs, thermal conductivity improvement, and their applications in buildings, as well as research gap identification. In section 3, the methodology is described, together with material preparation and experiment, as well as its criteria of assessment. The fourth section deals with the architecture of the proposal and experiment description. Section 5 focuses on comparing different formulations' performance.

II. Background and Previous Studies

Due to its renewable supply, degradability, and potential for energy storage, bio-based phase transition materials have been the subject of much research (Boussaba et al., 2019; Łapka et al., 2024). Naturally available fatty acids, vegetable oils, and biological substances have been explored as possible phase change materials for temperature stabilization indoors. They possess certain qualities that enable them to store extra heat in case of high temperatures and release the same when temperatures outside are low. Such materials can be used to create building wall, ceiling, roof, and insulation compositions. Earlier researches on organic phase change materials have established that latent heat capacity and melting point are significant parameters for evaluating their utility. With proper transition temperatures, such materials will increase indoor temperature comfort by stabilizing indoor temperatures. Nevertheless, certain bio-based materials have relatively poor thermal conductivity, resulting in slower heat transfer and thermal charge-discharge rates. In order to address this problem, scientists have been working on conductive additives such as expanded graphite, graphene-based substances, metals, and other carbon-based structures. One more interesting area in the field is encapsulation. The microencapsulation process as well as creation of shape-stabilized composites can help minimize leakage during melting and ensure better compatibility with construction materials. However, because the share of the matrix increases when an additive is added, the latent heat capacity may be reduced. One more aspect that needs to be taken into account when considering the long-term use of the material in buildings is its thermal stability. Heating and cooling cycles can affect phase change temperatures, latent heat storage, and material composition. Differential scanning calorimetry, thermal conductivity testing, and thermogravimetric analysis are the most common methods used in the assessment of these properties.

However, in spite of all these advancements, it becomes difficult to achieve an equilibrium among these factors such as the renewable material constitution, thermal conductivity, heat capacity, leak-proof property, and stability. Therefore, comparative experimentation on the formulations of bio-based PCMs is necessary for the optimized selection of thermal energy storage materials.

Existing Knowledge Gaps

Even though there have been studies carried out on renewable PCMs, encapsulation techniques, and increasing thermal conductivity, certain shortcomings still exist. Most of the studies are focused on specific

properties of materials instead of looking at the overall impact of thermal conductivity, latent heat storage capacity, and efficiency of energy storage. The impact of conductivity enhancing agents on thermal energy storage performance also needs comparative studies. In addition, it is not enough focus on thermal cycling durability, leakage tolerance, and operation under building conditions through the same experimental procedure. Without a comparative study, it is hard to determine bio-based PCMs which can be used in construction practice. Hence, this paper presents a systematic evaluation methodology.

III. Experimental Procedure

Using material production, thermal measurement, and comparison, this methodology examines the thermal conductivity and thermal energy storage characteristics of biobased phase change materials. There are three different types of biobased PCMs that will be chosen for their thermal conductivity and effect of additives.

Material Selection and Preparation

Bio-sourced fatty acid-derived materials and oil derived materials are selected as main PCMs. There are three formulations that include bio-source PCMs in pure form, bio-source PCMs with expanded graphite, and bio-sourced PCMs with suitable matrix. Mixing of these materials is done under controlled heating process to obtain a uniform distribution. Shape stabilization or encapsulation may be considered for avoiding leakage during phase change.

Experimental Characterization

The prepared samples are analyzed by DSC for determining their melting temperature and latent heat capacity. The thermal conductivity of the samples is analyzed using a thermal conductivity analyzer. Thermogravimetric analysis (TGA) technique is used for analyzing thermal degradation and stability of the materials. Thermal reliability analysis is performed by repeatedly heating and cooling the sample. The data obtained from these tests is compared based on energy storage efficiency, improved conductivity, and latent heat storage.

Performance Evaluation Parameters

The parameters taken into consideration include:

- Thermal Conductivity (W/m.K)
- Latent Heat Capacity (kJ/kg)
- Melting Temperature (°C)
- Energy Storage Efficiency (%)
- Thermal Stability and Degradation Temperature.
- Latent Heat Storage Efficiency After Thermal Cycling (%)

The energy storage capacity may be found from Equation 1.

$$Q = mC_p\Delta T + mL \qquad (1)$$

Where:

- Q = total stored thermal energy (J).
- m = mass of PCM (kg).
- C_p = specific heat capacity (J/kg·K).
- ΔT =temperature difference (K).
- L = latent heat capacity (J/kg).

Proposed Architecture

The suggested architecture involves five interconnected stages in order to examine the performance of bio-based PCMs in sustainable constructions. At first, bio-based materials will be chosen and processed in order to obtain various PCMs formulas. Then, the obtained samples will be treated with the process of composite preparation and conductivity improvement through the use of proper supporting additives. Further, the thermal characterization will be done with the help of DSC, measurement of thermal conductivity and TGA. All experimental measurements will be used at the performance evaluation stage, when thermal conductivity, latent heat capacity, energy storage efficiency and thermal stability will be compared. Finally, the obtained formula will be used to examine its application in construction envelope to minimize indoor temperature fluctuations and need for heating/cooling.

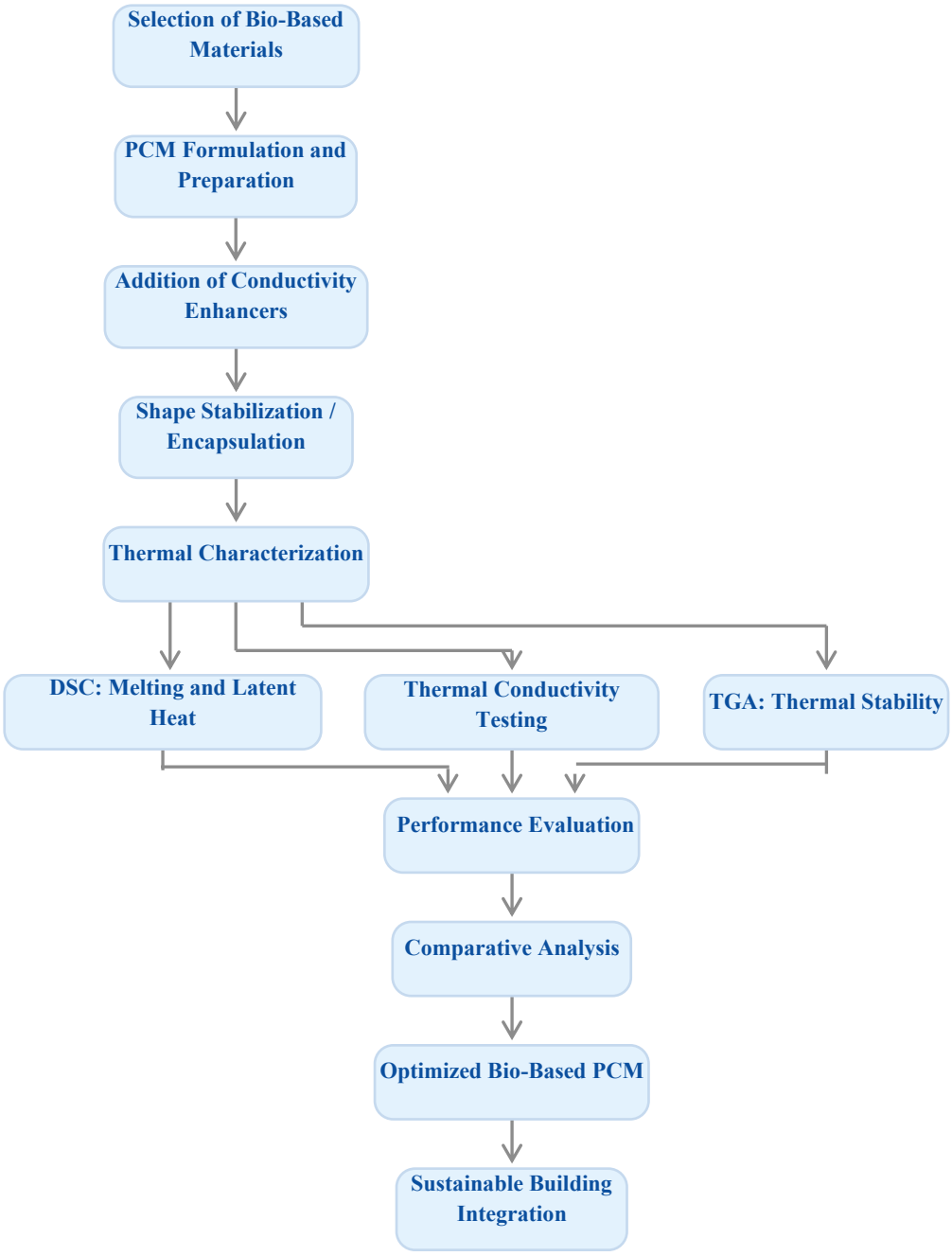


Figure 1: Proposed Methodology Pipeline for Bio-Based Phase Change Material Investigation

Figure 1 shows the experimental process flow used for investigating the bio-based PCMs, which includes material selection, formulation, conductivity improvement, and shape stabilization. Thermal analysis by DSC, conductivity tests, and TGA help in conducting comparisons and selecting the appropriate materials.

IV. Thermal Conductivity and Energy Storage Performance Analysis

Thermal Conductivity Enhancement of Bio-Based PCMs

The thermal conductivity of a PCM is one of the key factors determining its heat transfer properties. Bio-based PCMs are usually characterized by relatively poor thermal conductivity, which may adversely affect the ability of such materials to absorb and emit thermal energy during the processes of melting and crystallization. As a result, there is a need to increase thermal conductivity while maintaining a sufficiently high latent heat capacity.

Additives that enhance heat transfer due to the creation of additional heat-conducting channels inside the PCM can be used to increase thermal conductivity. In particular, expanded graphite can be mentioned since its porous structure provides PCM retention in addition to the creation of additional heat-conducting channels. Nevertheless, excessive use of the additive will lead to a decrease in the volume of the PCM itself.

The evaluation will focus on the thermal conductivity of three formulations that were tested under identical experimental conditions. The first formulation is the untreated bio-based phase change material. Expanded graphite is present in the second formulation. The third formulation combines conductivity enhancers, a matrix, and a bio-based phase change material. The impact of creating composite materials on thermal conductivity performance is assessed by comparing conductivity measurements of the three formulations. The results will aid in choosing the right building envelope material.

Energy Storage Efficiency and Building Application Performance

Energy storage performance affects the effectiveness of the bio-based PCMs in storing and releasing energy during phase changes. Latent heat capacity is the amount of energy that can be either released or absorbed without a significant change in temperature during the process of melting or solidification. A good PCM would require a melting point similar to the thermal regulation range indoors. Because of this, the material can store extra energy from hotter temperatures and release that energy when the temperature drops.

The energy storage performance for each formulation can be evaluated based on the latent heat capacity, melting point, and thermal cycling. Enhancement of thermal conductivity is another criterion for selection as an improvement in heat conduction may improve energy storage and release rates. However, enhanced thermal conductivity does not necessarily mean increased storage capacity. The amount of active PCM and latent heat retention is also important.

These bio-based PCMs can be used in the manufacturing of wallboards, ceilings, insulating layers, and other construction modules when developing buildings. The thermal storage capability of such materials might help in reducing the fluctuation of indoor temperatures while moderating extreme conditions of heating and cooling needs. Several cycles of heating and cooling tests are needed to check whether the properties of such materials remain stable during their continuous usage. Heat transfer, thermal storage capability, and stability provide an adequate foundation for the usability of such materials in sustainable building construction.

Comparative Experimental Results

Table 1 shows the comparison of the energy storage performances of three PCM formulations derived from biogenic sources. It is clear that pure PCM has the highest latent heat capacity while expanded graphite has high thermal conductivity. The composite material performs better in all parameters due to balanced energy storage and transfer performance.

Table 1: Comparative Thermal and Energy Storage Performance of Bio-Based PCM Formulations

Performance Parameters	PCM-A: Pure bio-based	PCM-B: Expanded graphite	PCM-C: Optimized composite
Thermal conductivity (W/m·K)	0.18	0.35	0.42
Latent heat capacity (kJ/kg)	185	172	165
Melting temperature (°C)	25.5	25.2	25.0
Energy storage efficiency (%)	76	84	88
Thermal cycling retention (%)	90	94	97
Leakage resistance (%)	82	91	96

Graphical Analysis

Thermal Conductivity Data of Three Bio-Based PCMs0 W/m·K0.15 W/m·K0.3 W/m·K0.45 W/m· KPure PCM Graphite PCM Optimized composite.

Figure 2 demonstrates the comparison of thermal conductivity of three bio-based PCMs with the help of a doughnut chart. The value of pure PCM is 0.18 W/m·K, while expanded graphite brings this value up to 0.35 W/m·K and 0.42 W/m·K in the case of the optimized composite.

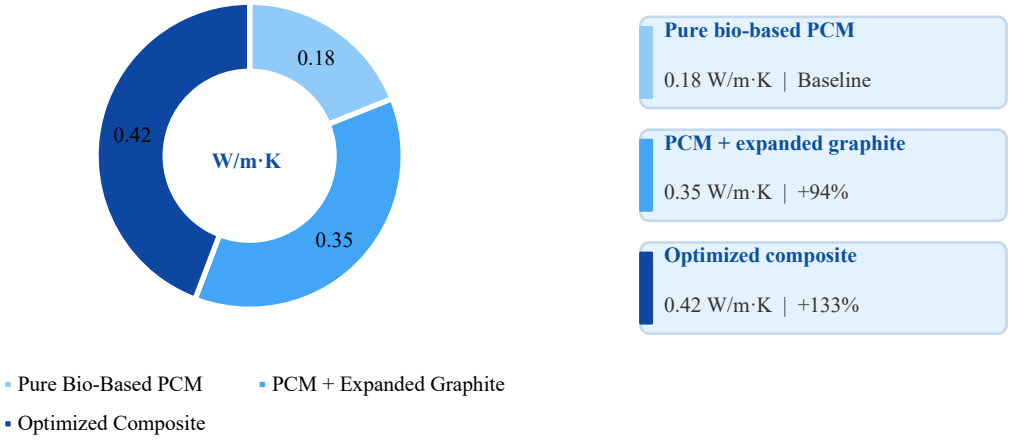


Figure 2: Thermal Conductivity Comparison of Different Bio-Based PCM Formulations

V. Results and Discussion

The comparative analysis shows that the use of conductivity-improving additives could be an efficient way to enhance the thermal properties of biological PCMs. Thermal conductivity of bio-based PCM is equal to 0.18 W/m·K and its latent heat capacity equals to 185 kJ/kg. Expanded graphite improves the value of thermal conductivity up to 0.35 W/m·K whereas optimized composite improves it up to 0.42 W/m·K. The value of latent heat capacity declines to 165 kJ/kg due to the presence of composite components. Optimized composite shows illustrative values of energy storage efficiency (88%) and thermal cycling efficiency (97%). Therefore, it becomes clear that increasing thermal conductivity together with maintaining latent heat capacity is crucial for the thermal energy storage. Optimized composite is capable of exhibiting promising properties of incorporation into the building envelope that could help to regulate the indoor temperature and decrease the need in heating and cooling.

Challenges in Bio-Based PCM Development

There are several challenges in integrating bio-based phase transition materials into sustainable structures. The low thermal conductivity of the material leads to the limitation of the heat exchange rate, influencing thermal charge and discharge rates. The latent heat of the system can be reduced due to the decreased amount of the active phase change materials if the additives that increase the thermal conductivity are used. The leakage of the melted substance can result in damaging the adjacent building materials. Thermal decomposition due to the cyclic thermal exposure will lead to the changes in the material properties, which will reduce its sustainability in time. Material compatibility should also be taken into account since the phase change materials should interact with construction materials properly while not affecting their characteristics. Besides, manufacturing costs of composite production, encapsulation, and thermal conductivity enhancement will limit the technology application on a large scale.

Future Recommendations

Further research must consider optimal design of bio-based PCM using different types of renewable biomass and conductivity enhancers. The amount of expanded graphite or other conductive materials should be varied to find out the most favorable ratio of thermal conductivity and latent heat storage. Microencapsulation and stabilization methods can be developed to reduce the risk of material leakage and increase durability. It is necessary to study the performance of the material during thermal cycling in realistic environmental conditions. The effect of PCM incorporation on building heating and cooling could be examined by means of building scale experiments and simulations in order to see how much impact PCMs will have on indoor temperature and total energy consumption. Life cycle assessment of the technology could be performed to determine environmental and manufacturing implications as well as material recyclability. Hybrid systems combining bio-based PCMs with renewable insulation material could be considered in future studies.

VI. Conclusion

The evaluation of thermal conductivity and energy storage characteristics of biobased phase change materials for environmentally friendly building is the focus of this study. The main goal of the investigation is the selection of renewable thermal energy storage materials that would help regulate indoor temperatures without using traditional heating and cooling systems. The novelty of the proposed research idea consists of the comparison of biobased PCM materials through the consideration of thermal conductivity enhancement, latent heat storage capability, leakage resistance, and thermal cycle stability in one research methodology. The methodology itself implies the selection of renewable biological materials, formulation of PCM composites, and thermal characterization through differential scanning calorimetry, thermal conductivity tests, and thermogravimetric analysis. This framework also evaluates melting temperature, latent heat capacity, energy storage efficiency, and thermal cycle performance. The comparison results show that the optimal PCM composite has thermal conductivity equal to 0.42 W/m·K, latent heat capacity of 165 kJ/kg, and energy storage efficiency of 88%, and thermal cycle retention is 97%. This study highlights how crucial it is to improve thermal conductivity while maintaining enough latent heat storage while creating bio-based materials for energy storage. This type of materials has applications ranging from being used in building walls, ceilings, roofs, and insulation parts. It is believed that incorporation of such materials can result into improved thermal comfort levels and stability of the indoor temperatures as well as overall building energy efficiency. The future research needs to focus on the following areas: conducting long-term experiments; perfecting encapsulation; optimizing additive amounts; and assessing the performance of buildings. Additionally, environmental life-cycle and manufacturing costs analysis will be required to make this technology economically feasible.

References

[1] Nalla, B. T., Subbiah, G., Das, S. N., Kumar, S., Swarnkar, S. K., & Kaliappan, N. (2025). Bio-based phase-change materials for thermal energy storage: Recent advances, challenges, and outlook. *Results in Engineering*, 107087.10.1016/j.rineng.2025.107087

[2] Manar, G., Shalaby, M., Bakar, M. S. A., Parveez, B., Najeeb, M. I., Hassan, M. K., ... & Alawad, M. A. (2025). Bio-based composites with encapsulated phase change materials for sustainable thermal energy storage: A review. *Polymers*, *17*(21), 2925. https://doi.org/10.3390/polym17212925

[3] Öztürk, G., Temiz, A., Hekimoğlu, G., Aslan, M., Demirel, G. K., Erdeyer, Ö. N., ... & Subaşı, S. (2024). Microencapsulated phase change material/wood fiber-starch composite as novel bio-based energy storage material for buildings. *Journal of Energy Storage*, *84*, 110911. 10.1016/j.est.2024.110911

[4] Zhao, J., Li, Y., Fang, X., Sun, J., Zhang, W., Wang, B., ... & Guo, H. (2022). High interface compatibility and phase change enthalpy of heat storage wood plastic composites as bio-based building materials for energy saving. *Journal of Energy Storage*, *51*, 104293. 10.1016/j.est.2022.104293

[5] Li, A., Yang, Y., Ren, Y., Wan, Y., Wu, W., & Zhang, H. (2024). Bio-based composite phase change material utilizing wood fiber and coconut oil for thermal management in building envelopes. *Journal of Cleaner Production*, *469*, 143177. 10.1016/j.jclepro.2024.143177

[6] Boussaba, L., Makhlouf, S., Foufa, A., Lefebvre, G., & Royon, L. (2019). vegetable fat: A low-cost bio-based phase change material for thermal energy storage in buildings. *Journal of building engineering*, *21*, 222-229.10.1016/j.jobe.2018.10.022

[7] Wang, C., Cheng, C., Jin, T., & Dong, H. (2022). Review on bio-based shape-stable phase change materials for thermal energy storage and utilization. *Journal of Renewable and Sustainable Energy*, *14*(5). https://doi.org/10.1063/5.0102005

[8] Nazari, M., Jebrane, M., & Terziev, N. (2020). Bio-based phase change materials incorporated in lignocellulose matrix for energy storage in buildings—a review. *Energies*, *13*(12), 3065. https://doi.org/10.3390/en13123065

[9] Naresh, R., Parameshwaran, R., Ram, V. V., & Srinivas, P. V. (2022). Study on thermal energy storage properties of bio-based n-dodecanoic acid/fly ash as a novel shape-stabilized phase change material. *Case Studies in Thermal Engineering*, *30*, 101707. 10.1016/j.csite.2021.101707

[10] Sawadogo, M., Benmahiddine, F., Hamami, A. E. A., Belarbi, R., Godin, A., & Duquesne, M. (2022). Investigation of a novel bio-based phase change material hemp concrete for passive energy storage in buildings. *Applied Thermal Engineering*, *212*, 118620. 10.1016/j.applthermaleng.2022.118620

[11] Łapka, P., Dietrich, F., Furmański, P., Sinka, M., Sahmenko, G., & Bajare, D. (2024). Experimental and numerical estimation of thermal conductivity of bio-based building composite materials with an enhanced thermal capacity. *Journal of Energy Storage*, *97*, 112943. 10.1016/j.est.2024.112943

[12] Palanti, S., Temiz, A., Köse Demirel, G., Hekimoğlu, G., Sarı, A., Nazari, M., ... & Terziev, N. (2022). Bio-based phase change materials for wooden building applications. *Forests*, *13*(4), 603. https://doi.org/10.3390/f13040603