



FABRÍCIO REZENDE FONTENELLE

**BAMBOO – PCM:
SYNERGY FOR THERMAL ENERGY STORAGE IN
BUILDING MATERIALS**

**LAVRAS - MG
2023**

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Tese apresentada à Universidade Federal de Lavras, como parte das exigências do Programa de Pós-Graduação em Ciência e Tecnologia da Madeira, área de concentração em Ciência e Tecnologia da Madeira, para obtenção do título de Doutor em Ciência e Tecnologia da Madeira.

Orientador
Prof. Dr. Saulo Rocha Ferreira – UFLA

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FABRÍCIO REZENDE FONTENELLE

**BAMBOO – PCM:
SYNERGY FOR THERMAL ENERGY STORAGE IN BUILDING MATERIALS.**

**BAMBU – PCM:
SINERGIA PARA ARMAZENAMENTO DE ENERGIA TÉRMICA EM MATERIAIS
DE CONSTRUÇÃO.**

Tese apresentada à Universidade Federal de Lavras, como parte das exigências do Programa de Pós-Graduação em Ciência e Tecnologia da Madeira, área de concentração Ciência e Tecnologia da Madeira, para a obtenção do título de Doutor.

APROVADO em 21 de dezembro de 2023.

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LAVRAS – MG

2023

Dedication

Paraphrasing Carl Sagan

*In the vastness of space and immensity of time, it is
my joy to spend a planet and an epoch with my
children Luan, Ravi and everyone I deeply love.*

Agradecimentos

Agradeço imensamente a todos que direta, ou indiretamente me ajudaram a realizar esse trabalho.

Agradeço principalmente ao meu orientador Prof. Saulo Rocha Ferreira, que com muita paciência e sabedoria me aconselhou e possibilitou sua realização, através do grupo GREEN-UFLA e a própria UFLA, instituição que me acolheu nessa jornada.

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Agradeço a minha linda companheira Nana que sempre esteve presente nos bons e nos maus momentos, aos meus filhos simplesmente por existirem e darem um sentido a isso tudo e aos meus pais, irmãos e amigos, todos que eu amo e me apoiaram na realização de mais essa etapa.

Aos professores, professoras e pesquisadores, que gentilmente compartilharam seus conhecimentos provenientes de muito esforço: M'hamed Yassin, Prof. Romildo Toledo Filho, Keoma Defaveri, Andrea Correa, José Benedito, Gustavo Tonoli, Tadayuki Yanagi, Francisco Gomes, Priscilla Abreu, Thiago Graboís, Rodolfo Giacomim, Otávio Gomes e Leopoldo Bastos, Daniel Pimenta, Laércio Jr, Lorrán de Sousa.

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Aos amigos Evaldo, Alice e Ricardo Teixeira.

Ao povo brasileiro que entende a importância da ciência e da tecnologia para exorcizar o negacionismo e fundamentalismo.

Epigraph

*"Be like bamboo. The higher you grow, the deeper
you bow."*

Chinese proverb.

RESUMO

Em um mundo em busca de sustentabilidade onde as construções possuem papel expressivo nos impactos ambientais, todas as pesquisas traçam um caminho relevante se buscam a eficiência ambiental das edificações, especialmente se atreladas ao uso de fontes renováveis. Nessa direção, esse trabalho buscou unir a biomassa lignocelulósica do bambu, com seus atributos vantajosos, tanto na fixação de CO₂ na atmosfera como por sua resistência físico mecânica, com a utilização de materiais de mudança de fase (PCM) e suas características térmicas notáveis. Nos climas tropicais, a alta incidência da radiação solar faz com que as envoltórias das edificações recebam fortemente tal energia e isso contribui para que materiais com comportamento térmico vantajoso sejam importantes para defesa do conforto ambiental, possibilitando redução do uso de condicionamento térmico. Esse é o caso dos PCMs cujo potencial eminente tem sido explorado pelas mais recentes pesquisas de ponta. Este trabalho teve por objetivo principal, portanto, desenvolver, analisar e avaliar o desempenho de protótipos produzidos com matriz de colmos de quatro diferentes e importantes espécies de bambu presentes na América do Sul, impregnados com material de mudança de fase PCM, principalmente através de caracterizações, ensaios comparativos e valorativos das qualidades dos objetos resultantes. Para apresentar esses processos e seus resultados e facilitar a compreensão, o conteúdo dessa tese foi dividido em duas partes principais, tendo a primeira parte por objetivo a apresentação geral da pesquisa e a segunda parte com a apresentação de três artigos com a exposição sucessiva dos experimentos realizados e seus resultados. O artigo 1 investigou a impregnação por PCM de colmos da espécie o de *Phyllostachys aurea* a fim de validar a hipótese sugerida, o artigo 2 comparou essa mesma espécie com mais outras três, *Bambusa tuldoidea*, *Dendrocalamus giganteus* e *Guadua augustifolia*, para analisar a influência dessa variação no comportamento térmico após a impregnação, e o artigo 3 apresenta um ensaio análise de variação térmica em túnel de vento expondo aos mesmos controles alguns materiais construtivos convencionalmente utilizado pela indústria para efeito comparativo. Esse estudo comprovou que é possível a impregnação por PCM em bambu em quantidade funcional para os efeitos térmicos desejados e também que as características específicas das espécies e fatores ambientais como o vento exercem influência sobre esse resultado.

Palavras-chave: Estocagem de energia térmica. Bambu. Pcm. Caracterização térmica. Biomassa lignocelulósica.

ABSTRACT

In a world seeking sustainability, where the construction industry plays a significant role in environmental impacts, all research endeavors are on a relevant path if they aim to enhance the environmental efficiency of buildings, especially when linked to the use of materials from renewable sources. In this context, this work sought to combine the abundant lignocellulosic biomass matrix of bamboo, with its advantageous attributes, such as its capacity to sequester carbon dioxide in the atmosphere and its physical-mechanical resistance, with the use of Phase Change Materials (PCMs) and their remarkable thermal characteristics. In tropical climates, the high incidence of solar radiation affects the building envelopes directly due to their exposure to significant climate variations and extremes, making materials with favorable thermal behavior important for environmental comfort and reducing the use of high-energy-cost thermal conditioning. This is the case with PCMs, whose potential has been explored by the latest cutting-edge research. The main objective of this work was to develop, analyze, and assess the performance of prototypes produced with bamboo culm matrix from four different and important bamboo species present in South America, impregnated with PCM, primarily through characterizations, comparative tests, and qualitative assessments of the qualities of the resulting objects. To present these processes and their results and facilitate understanding, the content of this thesis was divided into two main parts. The first part aimed to provide an overall presentation of the research, while the second part presented three articles with the successive exposition of the experiments conducted and their results. The article 1 investigated the PCM impregnation of *Phyllostachys aurea* bamboo culms to validate the suggested hypothesis. Article 2 compared this same species with three others, *Bambusa tuldoidea*, *Dendrocalamus giganteus*, and *Guadua augustifolia*, to analyze the influence of this variation on thermal behavior after impregnation. Article 3 presented a thermal variation analysis in a wind tunnel, also exposing some conventionally used building materials for comparative purposes. This study confirmed that PCM impregnation in bamboo is possible in a quantity that functions for the desired thermal effects and that the specific characteristics of bamboo species and environmental factors such as wind influence this outcome.

Keywords: Thermal energy storage. Bamboo. Pcm. Thermal characterization; Lignocellulosic biomass.

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NOMENCLATURE

TES	Thermal energy storage systems
STES	Sensible Thermal Energy Storage
LTES	Latent Thermal Energy Storage
TCS	Thermo-Chemical Energy Storage
PCM	Phase Change Material
SDG	Sustainable Development Goals
UN	United Nations
GWP	Global Warming Potential

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FIRST PART - INTRODUCTION

1. Project Motivation

Humanity's connection with bamboo spans millennia, as it has served as a versatile tool, a source of nourishment, and a fundamental building material. Throughout history, people have harnessed the potential of bamboo to craft an array of items, ranging from weaponry to musical instruments and due to its admirable characteristics, it has been honored in paintings, poems, and even by great spiritual masters of the ancient East as an exceptional metaphor for the significant challenges presented in the winding journey of life. This enduring relationship between bamboo and humans has been a conduit for the exchange of numerous lessons and it has not only captivated us with its practicality but also with its graceful beauty and remarkable durability (CHAVES, 2017, FARRELLY, 1996, JIAYAN, 2014, SLOCUM, 2007, VILLEGAS, MARCELO. RESTREPO, 2001):

Facing today's challenges in the pursuit of sustainable development, bamboo, as a renewable natural resource, can significantly reduce the environmental impacts of the construction industry. This reduction can be achieved through the promotion of its use because this material seems to have been tailor-made for construction applications. The availability of this resource, combined with its ease of propagation, rapid maturation for harvesting, and suitable physical-mechanical properties (DARABANT, RAI, *et al.*, 2016, PALANI, V., GOUTHAM, P., AYYAPPADASAN, R., & PRAVEENA, 2020), make it suitable for construction applications as a replacement for materials that have a more significant impact on the environment. These materials often originate from non-renewable resources or native plant resources that are exploited without proper management and conservation.

Reforestation has been recommended as one of the measures to reduce the greenhouse effect caused by increasing carbon dioxide concentrations in the Earth's atmosphere (LOBOVIKOV, SCHOENE, *et al.*, 2012, SONG, PENG, *et al.*, 2020). Within this philosophy, carbon sequestration by fast-growing forest systems like bamboo is an excellent alternative, considering that Brazil has highly favorable environmental conditions for this purpose. This plant family exhibits exceptional growth (GAN, CHEN, *et al.*, 2022), producing biomass at a better rate when compared to timber (FU, JIANG, *et al.*, 2014, TROYA MERA, XU, 2014), using the same cultivation area. Bamboo can be used in the construction industry due to its

suitable physical-mechanical properties (LAKKAD, PATEL, 1981), providing an interesting alternative to materials commonly used in the market today, such as extracted wood, steel, and reinforced concrete.

On the other hand, the rapid surge in global energy demand, propelled by technological advances, economic growth, and population expansion in recent decades (DESHMUKH, SAMEERODDIN, *et al.*, 2023), has sparked substantial concerns. The "Net Zero Emissions by 2050 Scenario" proposed by the International Energy Agency (INTERNATIONAL ENERGY AGENCY, 2021) underscores the crucial role of energy efficiency in ensuring that clean energy sources can meet the escalating demand for energy services. This scenario envisions that by implementing policy and technological measures in the building sector, we can swiftly and significantly improve the energy efficiency of buildings. Large-scale retrofit initiatives in line with zero-carbon building standards (LIU, Yinshan, XUE, *et al.*, 2023) are pivotal in this mission. Consequently, the development of technologies geared toward enhancing energy efficiency is imperative in mitigating the repercussions of global warming and establishing sustainable energy consumption practices.

Continuing in the same direction, cutting-edge research on improving the thermal capacity and efficiency of materials has been very successful in exploring the potential of Phase Change Materials (PCMs) when it comes to the possibility of Thermal Energy Storage (TES). It emerges as a prominent method for enhancing the energy efficiency of buildings by utilizing this storage capacity helping to smooth out temperature fluctuations, reducing the need for climate adjustments in spaces due to natural climate variations.

According to (CABEZA, CASTELL, *et al.*, 2011), the main advantage of Latent Thermal Energy Storage is the high storage density over small temperature ranges, making it suitable for both heating and cooling of buildings. It can be incorporated as a passive system or in active climate control systems. Many research studies have sought structures that could serve as receptacles for PCMs to contain these substances in their various physical states, which are essential for their thermal efficiency. Among these receptacles, porous materials have shown an interesting capacity (ZHANG, Shuai, FENG, *et al.*, 2021). And in light of this, organic materials like naturally porous plant tissues have become an interesting option to be explored with the intention of fulfilling this role, enabling the synergy of environmentally beneficial properties.

1.1. Study objectives

The present research aimed to precisely combine the capabilities and potentiality inherent in lignocellulosic materials such as naturally porous bamboo culms with the potential for thermal efficiency induced by impregnation with phase change materials in its anatomical structure, therefore our central hypothesis was:

It is believed that it is possible to use the natural anatomical porosity of bamboo culms from widely available species as a repository for phase change materials in a sufficient quantity to provide functionality in terms of the inherent thermal efficiency of PCM in the resulting object, and that this object is functional for use in building envelope or weather protection elements in constructions.

Taking into consideration the facts stated above, the following key questions guided this research:

1. Is it possible to utilize the natural porosity of bamboo culms as a repository for phase change materials, considering that it's possible to impregnate other substances into this material?

2. If PCM can be impregnated into bamboo, will it be in sufficient quantity to provide functionality for the inherent thermal efficiency of PCM in the resulting object?

3. Which bamboo species would be most suitable for this purpose, considering impregnation capability, as well as local abundance and availability?

4. Do the density and other physical and anatomical characteristics of the bamboo takes influence in the impregnation content, and can the impregnation method result in a higher PCM content in the anatomical porosity of bamboo culms?

5. Does the prototype morphology used for functionality as a construction material of PCM-impregnated bamboo culms influence this process?

6. With varying temperature and proper impregnation, it is expected that the thermal phenomenon due to PCM use becomes identifiable, but other aspects, such as the air flow rate, can affect this phenomenon.

To investigate and address these questions, the following key objectives were defined:

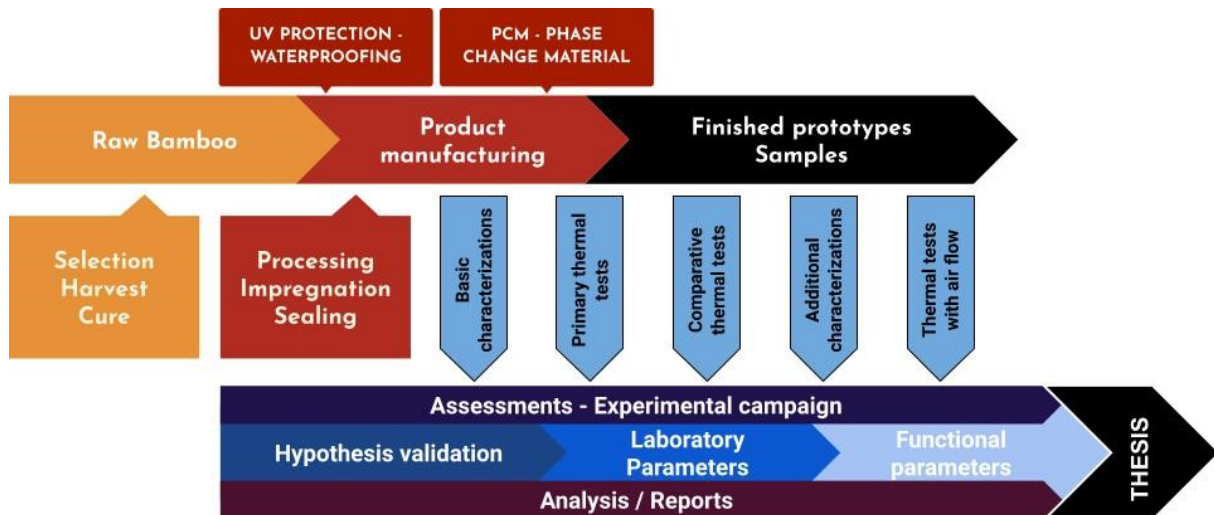
- 1. Develop prototypes for construction material for use in building envelopes that are functional and capable of effective thermal energy storage, using bamboo and PCM through simplified processes with minimal processing.*
- 2. Evaluate and compare different bamboo species of wide availability impregnated with phase change material (PCM).*
- 3. Compare prototypes produced with bamboo/PCM with conventional materials in the construction market."*

1.2. The structure of the thesis and the applied methodological strategy

This research was based on field activities for the collection of materials in rural sites in the municipalities of Carrancas and Juiz de Fora in the state of Minas Gerais, southeastern Brazil. Bamboo culms from various species were harvested under suitable conditions for the purpose of the investigation and in accordance with the most appropriate standards. Activities were also conducted in workshops with woodworking equipment, where the sample units were manufactured in various formats, and the necessary executive procedures were carried out for subsequent analyses.

In the laboratory, the resulting material was further evaluated and tested in the form of test specimens under various conditions and controlled environments. Simulations closer to real exposure to weather conditions were also performed for a better assessment of the various qualities of interest. Small samples in specific formats were also produced using suitable equipment for packaging, aiming at more delicate chemical and structural analyses. The diagram in Figure 1 shows the general research procedures, summarizing the production and analysis phases that this research was dedicated to.

Figure 1 - Diagram of general procedures and methodological strategy.



Source: Author (2023)

The content of this thesis is presented and subdivided as follows:

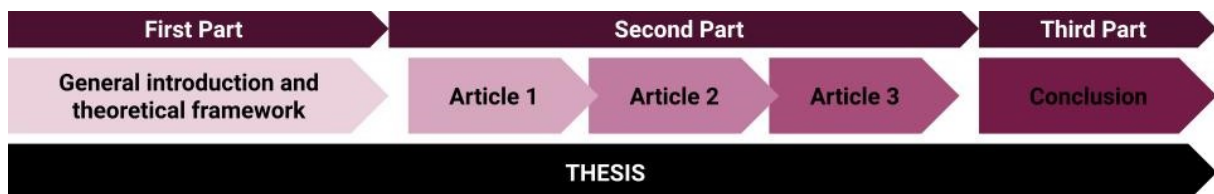
The first part aims to introduce the reader to the object of study of this thesis, providing tools to help understand the topics covered. It consists of 3 sections, including the introduction, a literature review or theoretical framework that aimed at contributing to a better understanding of the work, and final considerations on the literature review.

The second part contains the three papers produced with reports of the investigations carried out, namely:

1. The first paper (Article 1) entitled "Bamboo-PCM: The use of *Phyllostachys aurea* culms as a receptacle for thermal storage through phase change material impregnation" investigated the impregnation of PCM into the culms of the mentioned species to verify the validity of the suggested hypothesis.
2. The second article (Article 2) entitled "Bamboo-PCM: The comparative study of four different species' culms as a receptacle for thermal storage through phase change material impregnation" compared the same species from the first article with three others, *Bambusa tuldoidea*, *Dendrocalamus giganteus*, and *Guadua augustifolia*, to analyze the influence of this variation on thermal behavior after impregnation.
3. The third article (Article 3) entitled "Bamboo-PCM: Comparative analysis of phase change material impregnated *Dendrocalamus giganteus* culm behavior exposed to thermal variation in a wind tunnel essay" presents an essay analysis of thermal variation in a wind tunnel, exposing conventional construction materials used by the industry to the same controls for comparative purposes.

Finally, the third part of the thesis contains the general conclusions of this research, followed by suggestions for future work. shows a summarized schematic of the thesis structure.

Figure 2 - Diagram of the Thesis structure.



Source: Author (2023)

1.3. Theoretical Framework

1.3.1. Challenges in the pursuit of sustainability in the construction

Since the second half of the 20th century, after a rapid development of science and technology, as well as unprecedented population growth, humanity has been observing with concern the possible consequences of the continued exploitation of resources to sustain the current culture of consumption at the same rate (BARBIER, BURGESS, 2017, HUANG, Ming-Hui, RUST, 2011, KLAASSEN, OPSCHOOR, 1991). A crisis of access to energy resources and the subsequent climate crisis due to global warming caused by human activities (CHEN, Shaoqing, KHARRAZI, *et al.*, 2020, QAZI, HUSSAIN, *et al.*, 2019) conducted in error are motivations that drive the search for increasingly effective solutions in the pursuit of the widely discussed sustainability, which boils down to meeting the needs of current generations without compromising the needs of future ones (BRUNDTLAND, 1987). When we consider all the Sustainable Development Goals (SDGs) advocated by the United Nations (UN), we can see the need to focus on research that is aligned with these parameters for global improvement (UNITED NATIONS - DEPARTMENT OF ECONOMIC AND SOCIAL AFFAIRS SUSTAINABLE DEVELOPMENT -, 2023) .

Of all human activities, the construction industry is known to have an extremely relevant role, particularly in the consumption of natural resources, energy, and the resulting environmental impacts (ORTIZ, CASTELLS, *et al.*, 2009, ZEA ESCAMILLA, HABERT, 2014) These three issues are already of great concern, but when considered in light of the rapid urbanization process of recent decades, it becomes clear that the need for high-performance construction materials designed for specific purposes is more urgent than ever. Furthermore, the high levels of CO₂ emissions from construction materials production represent a global problem (MUNCH-PETERSEN, LEWIS, 2022). In this regard, biobased construction materials have the advantage of being not only renewable but also capable of sequestering CO₂ during their growth (RIAÑO, N.M., LONDOÑO, X., LÓPEZ, Z , GÓMEZ, 2002), as well as storing it during their use phase.

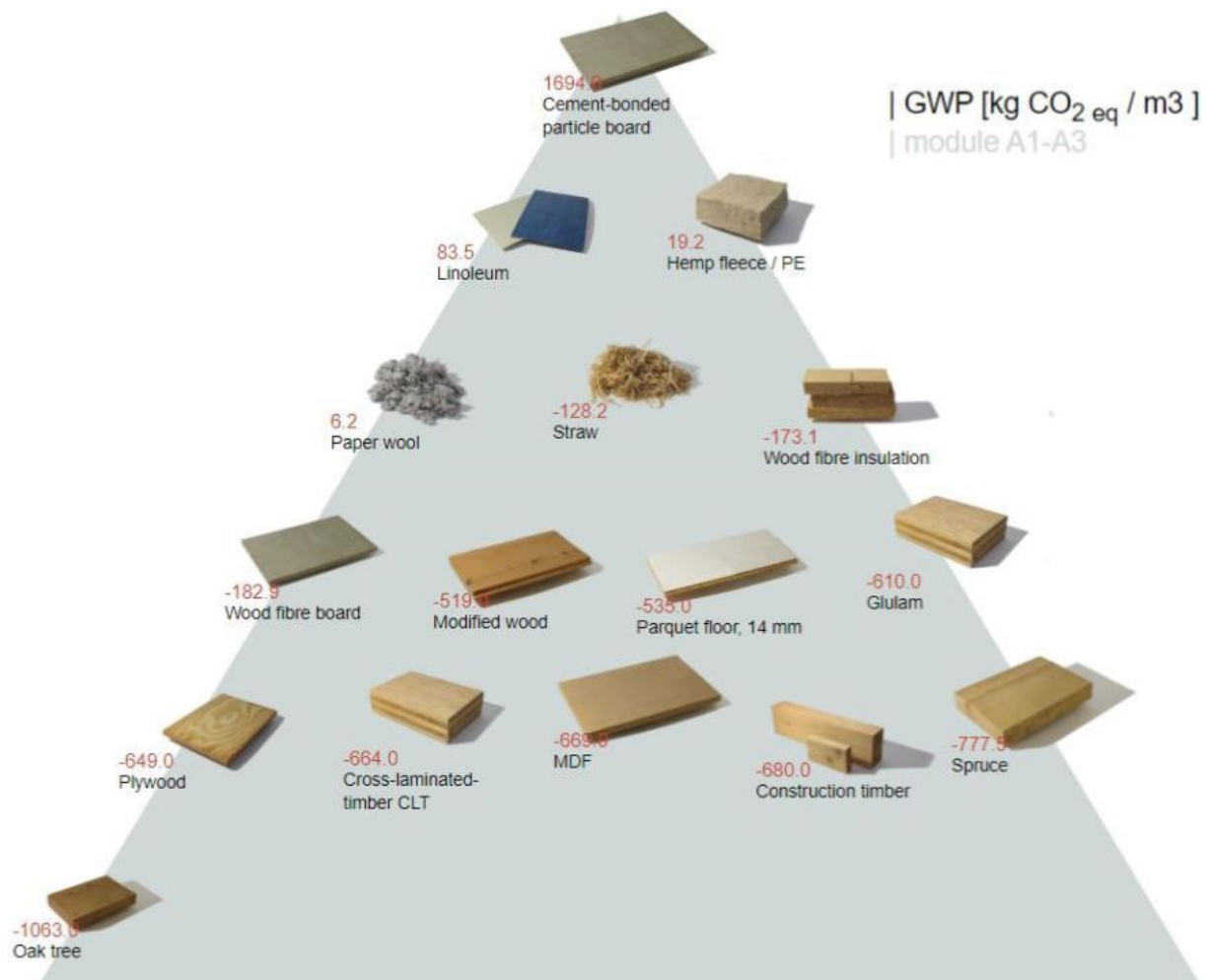
Figure 3 - Pyramid of building materials: overview of the CO₂ impact of materials for your construction project, interactive version available at <https://www.materialepyramiden.dk/>



Source: (CINARK, 2023)

In Figure 3 you can see the Pyramid of Building Materials developed by (CINARK, 2023). This pyramid assesses commonly used building materials based on their Global Warming Potential (GWP), providing an overview of the environmental impact of your construction project. GWP, or "carbon footprint," measures how much heat-trapping capability a given amount of gas has in the atmosphere compared to the same mass of CO₂. Higher GWP values indicate a greater impact on global warming. Organic materials, in this context, have negative GWP values, meaning they absorb more greenhouse gases than they emit during their production validating, therefore, the encouragement of its use. In Figure 4, it is possible to observe in more detail how materials based on lignocellulosic organic raw materials present much more advantageous results in terms of their qualities for addressing global warming.

Figure 4 - Pyramid of construction materials and the impacts of inputs based on lignocellulosic organic raw materials in isolation.



Source: (CINARK, 2023)

An eventual transition to a lasting sustainable construction culture involves equal care for the three aspects of the so-called sustainability tripod (LIMA, DE MIRANDA, *et al.*, 2019), acting responsibly in social, economic, and environmental matters. Concepts such as choosing so-called "appropriate" construction technologies (RODRIGUES, BARBIERI, 2008), the need to make them effectively accessible to the majority of the population, primarily involve concerns about the possibility of self-construction or facilitating production for the less privileged layers of society, taking into account concepts of low technology and minimal processing, as well as the availability and local availability of the necessary resources.

Therefore, it is necessary for research into genuinely more sustainable construction materials to consider that high complexity or excessive demand for processes, as well as high manufacturing costs, will not make these so-called "new technologies" accessible to a sufficient

percentage of the predominantly poor global population (VAN LENGEN, 2021) for positive impacts to be effectively relevant in addressing the aforementioned crises. From this perspective, concepts such as *low-tech smart materials and systems*, self-production, and minimal processing are interesting parameters to guide choices in the development of materials in the context of more contemporary research, especially when located in regions away from centers of wealth (ABDELMOHSEN, ADRIAENSSENS, *et al.*, 2019, GOUGH, 1996, HIRSCH-KREINSEN, 2008, VON TUNZELMANN, ACHA, 2006). In Figure 5 An illustrative graph depicts the search for a sustainable transition.

Figure 5 - Illustrative graph of the transition to sustainable processes in human activities.



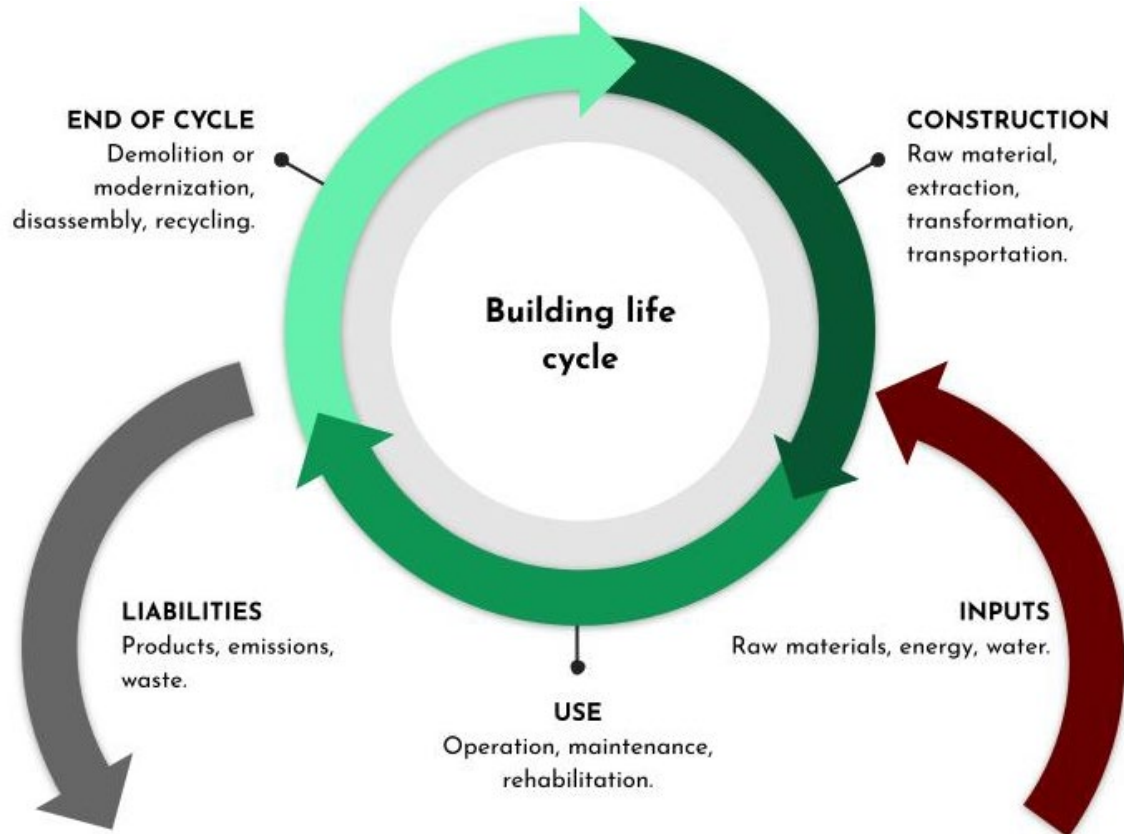
Source: (STEPHENS, 2022)

1.3.1.1. Building life cycle

In order to effectively assess the impact that buildings generate, there is a field of work and research that focuses on analyzing the life cycle of buildings and materials. This includes understanding all the processes that directly or indirectly are part of the large chain that allows

the construction to be executed, as well as its operation (ANTUNES, GHISI, 2021, SILVA, Marcos Antonio do Rosario da, BLANCO, *et al.*, 2020).

Figure 6 - Illustrative diagram for the building life cycle.



Source: Author (2023)

Given these issues, it is understood that the successive stages that make up this process, as illustrated in Figure 6, create the need for various inputs, such as raw materials, energy, and water, as well as the necessary transformation work for their feasibility. It is also understood that these processes generate numerous liabilities, such as emissions of various types of waste. These stages have quantifiable or non-quantifiable costs in economic, energy, environmental, and social terms, and these costs are also distributed chronologically in the construction (execution), operation (use, maintenance), and end-of-life (demolition, renovation) phases of the building (ABD RASHID, YUSOFF, 2015, BLENGINI, DI CARLO, 2010, KOVACIC, ZOLLER, 2015, SHARMA, Aashish, SAXENA, *et al.*, 2011).

More specifically, regarding the energy cost of buildings, we can primarily mention the energy content embedded in the building as a result of its materials and processes, as well as the energy cost of the daily operation required for its everyday use. This includes the use of systems for pumping, elevator operation, lighting, and thermal conditioning. This last topic has

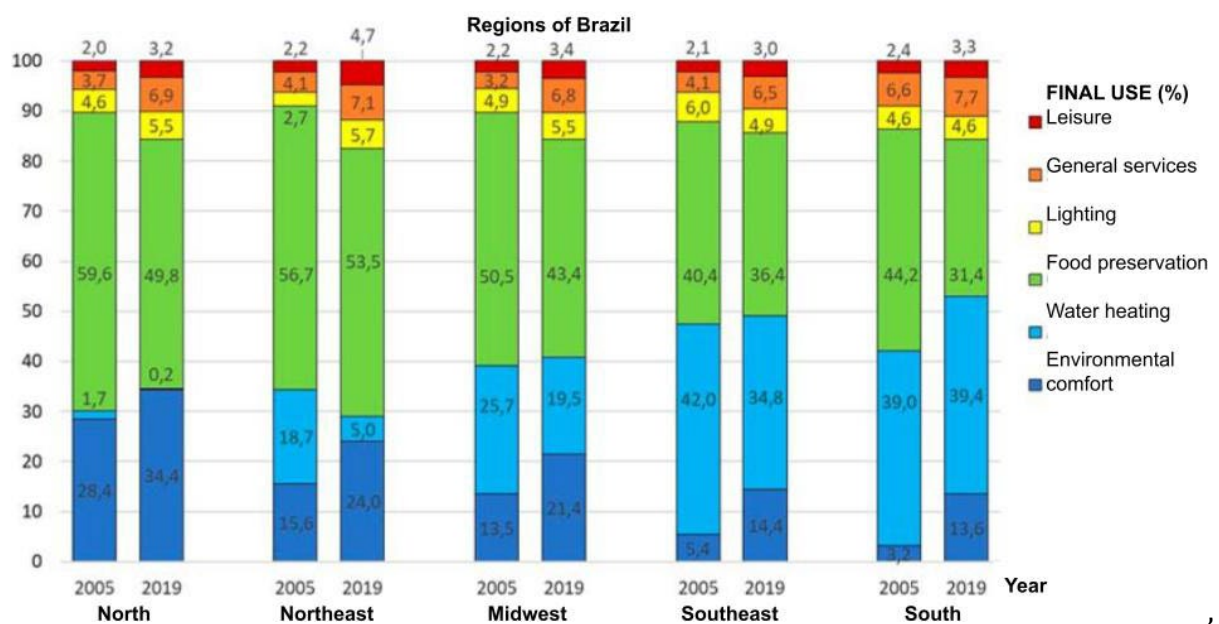
been recognized as highly relevant precisely because it represents a cost that is closely tied to architectural design and material choices. Its influence is directly related to the subsequent required consumption of energy (SCOLARO, TEIXEIRA, *et al.*, 2022).

1.3.1.2. Environmental Comfort in Buildings and Energy Efficiency

The study of environmental comfort in buildings is of enormous relevance because it effectively deals with ergonomics, which can be defined as the best concrete adaptation of the space or location of an activity to the person who performs it (ATTAIANESE, 2017, SARAIVA, DE ALMEIDA, *et al.*, 2018). Therefore, it offers the possibility to assess the various aspects that make the use of a construction as compatible as possible with its function (MALTA, RABBI, *et al.*, 2022).

Among the various aspects analyzed in the issues of environmental comfort, thermal comfort and lighting comfort are where the greatest possibilities exist to explore energy efficiency. This is because the use of artificial lighting, and especially heating and cooling systems, has significant and increasing energy consumption, as illustrated in the Figure 7 - Structure of residential electricity consumption by end use, by equipment category, by geographic region in the Brazilian territory in 2005 and 2019 (%). Figure 7 (ABRAHÃO, SOUZA, 2021). A clever relationship between architectural design and the natural environment can significantly improve this correlation (LAMBERTS, DUTRA, 2004).

Figure 7 - Structure of residential electricity consumption by end use, by equipment category, by geographic region in the Brazilian territory in 2005 and 2019 (%).



Source: (ABRAHÃO, SOUZA, 2021) Edited by the Author (2023)

In regions where there are extreme climatic conditions, both for low temperatures and excessive heat (as can be observed in Figure 7, the proportionality of energy consumption for environmental comfort in buildings in the northern region of Brazil, located in the equatorial zone, for example), the relevant choices in building construction have a significant influence on how thermal comfort will be achieved in their interior spaces. These choices practically determine whether or not there will be a need to use active systems with energy costs to adapt the usability of the space (ALCHAPAR, CORREA, *et al.*, 2014, CHAPPELLES †, SHOVE ‡, 2005, HALL, 2010, RUPP, VÁSQUEZ, *et al.*, 2015).

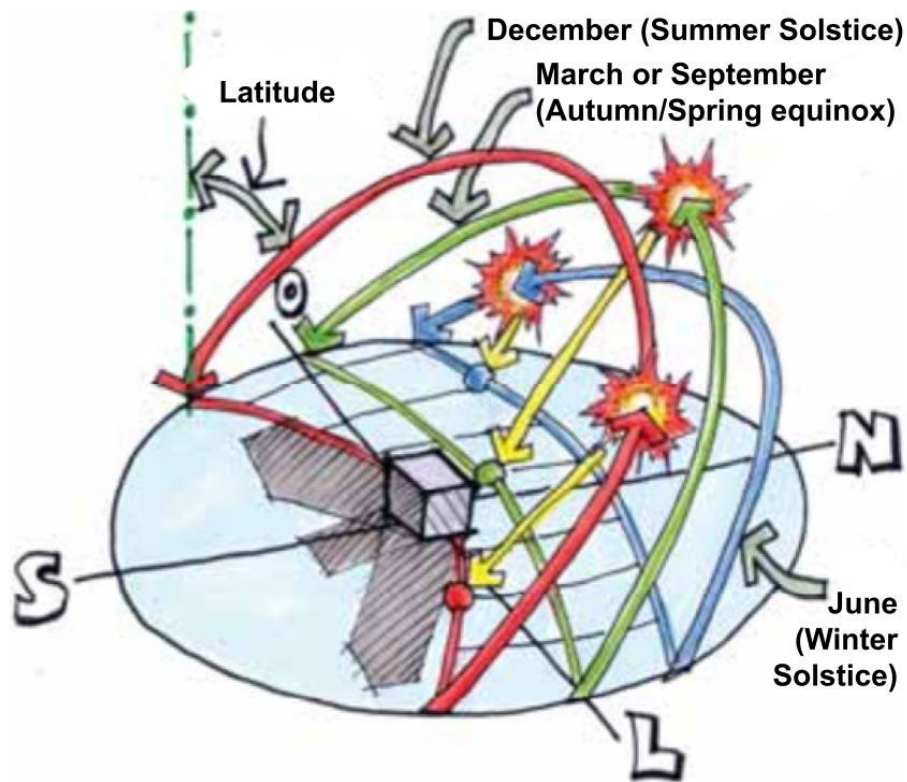
1.3.1.3. Envelope and bioclimatic zone, environmental comfort zone

Primarily, in the context of buildings, the main elements that can lead to an efficient relationship between the indoor and outdoor environment to achieve good thermal comfort are the enclosures, both on the vertical and horizontal planes. Therefore, the walls, roof, and the ground floor that contacts the existing ground, which can be referred to as the building's envelope, are the key components in a building that determine its comfort (MIRRAHIMI, MOHAMED, *et al.*, 2016, OLIVEIRA, Andréia Cardoso de, 2013, SADINENI, MADALA, *et al.*, 2011).

Regions around the world with human habitation exhibit a vast variety of climates and specific peculiarities. However, there are similarities that define bioclimatic zones with related characteristics, suggesting individual, particular solutions for mitigating these aspects concerning buildings (OLIVEIRA, Lutércia M. F. de, YANAGI JUNIOR, *et al.*, 2006, WILLIAM, SUÁREZ-LÓPEZ, *et al.*, 2021).

In the specific case of Brazil, as a country with a tropical climate, primarily located between the tropics, it's observed that solar radiation, the main carrier of thermal energy, occurs at much more vertical angles than in regions with higher latitudes. This situation underscores the even greater importance of building envelopes in these regions (ASLANI, BAKHTIAR, *et al.*, 2019). The Figure 8 illustrates the sun's path between solstices and equinoxes in regions with latitudes like those in Brazilian territory.

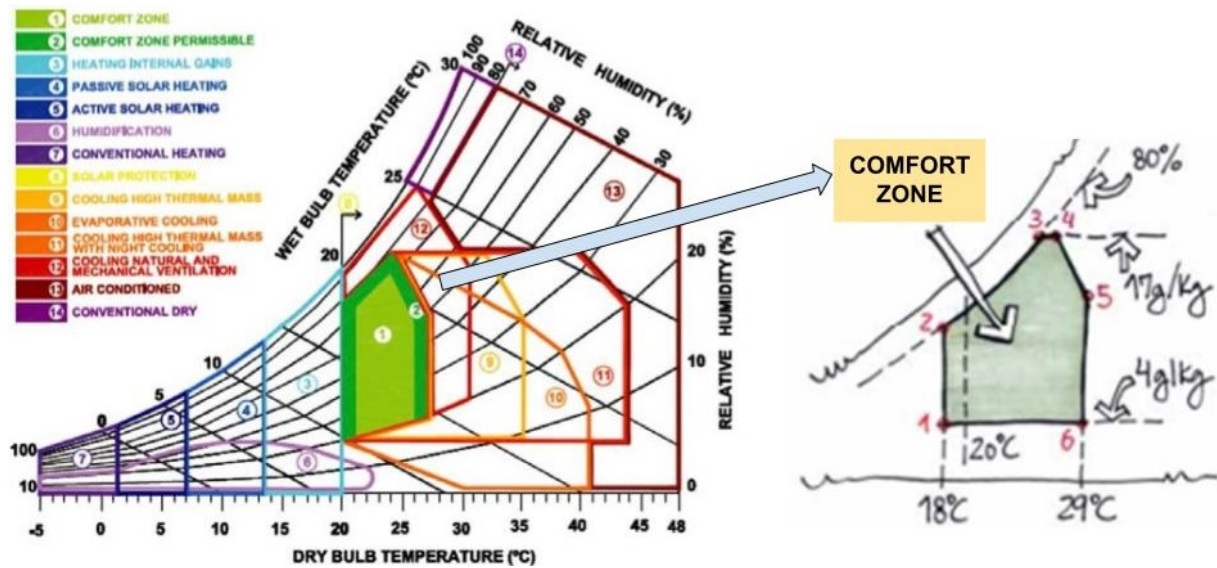
Figure 8 - Path of the sun at solstices and equinoxes in the Southern Hemisphere



Source: (LAMBERTS, GHISI, *et al.*, 2000) Edited by the Author (2023)

Environmental comfort, in general, is not solely related to temperature but also to various factors such as ventilation and relative humidity, with considerations including local clothing requirements, among other aspects. However, there are temperature and average relative humidity ranges within which various studies have predominantly shown greater human well-being, defining what is known as the comfort zone (FROTA, 2006, KUMAR, Sanjay, MATHUR, *et al.*, 2016, MACFARLANE, 1958).

Figure 9 - Psychrometric diagram of Givoni and limits of the comfort zone



Source: (LAMBERTS, DUTRA, 2004, VADOUDI, 2018) Edited by the Author (2023)

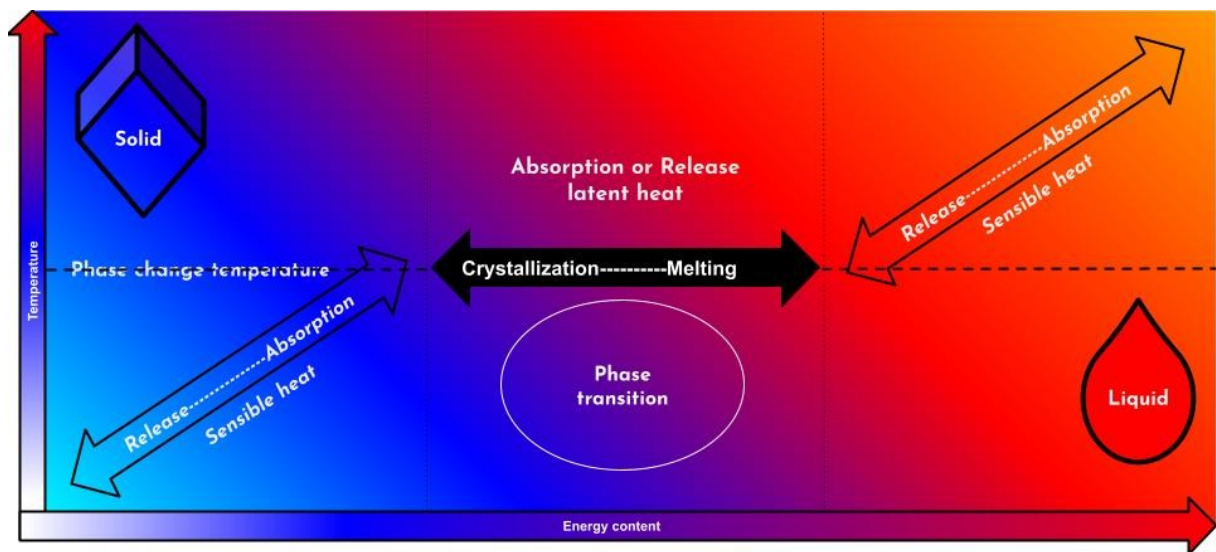
Figure 9 displays the bioclimatic psychrometric chart by Givoni adapted for Brazil, along with the constructed comfort zone (LAMBERTS, DUTRA, 2004, VADOUDI, 2018). This chart relates air temperature and relative humidity and indicates various operational zones with their respective strategies to mitigate the negative impacts of the climate. The limitations of the environmental comfort zone are also visible. These limitations suggest that people are likely to feel comfortable within temperatures between 18°C and 29°C (XAVIER, 1999), considering various other factors. This range is generally considered to be suitable, reflecting moderate human satisfaction with the surrounding thermal environment (LAMBERTS, GHISI, *et al.*, 2000, OLIVEIRA BORGES, CARLOS NACIMENTO, *et al.*, 2022).

1.3.2. PCMs - *Phase Change Materials*

Substances, in general, have a molecular arrangement that differs significantly in the various possible states of the material. When there is a phase change due to a temperature change that prevents the previous state from remaining, there is a reorganization of intermolecular chemical bonds that, when modified, require an energy movement in both the endothermic and exothermic directions, depending on the direction of this transition (SHARMA, Atul, TYAGI, *et al.*, 2009).

In practice, phase change materials, therefore, at their melting or evaporation points, solidification or condensation, continue to absorb or release heat without, however, changing their temperatures for a certain period, resulting in a latent heat input, as seen in the Figure 10, with a "plateau" in the middle (KHAN, KHAN, *et al.*, 2016, MAXA, NOVIKOV, *et al.*, 2017, SOARES, COSTA, *et al.*, 2013).

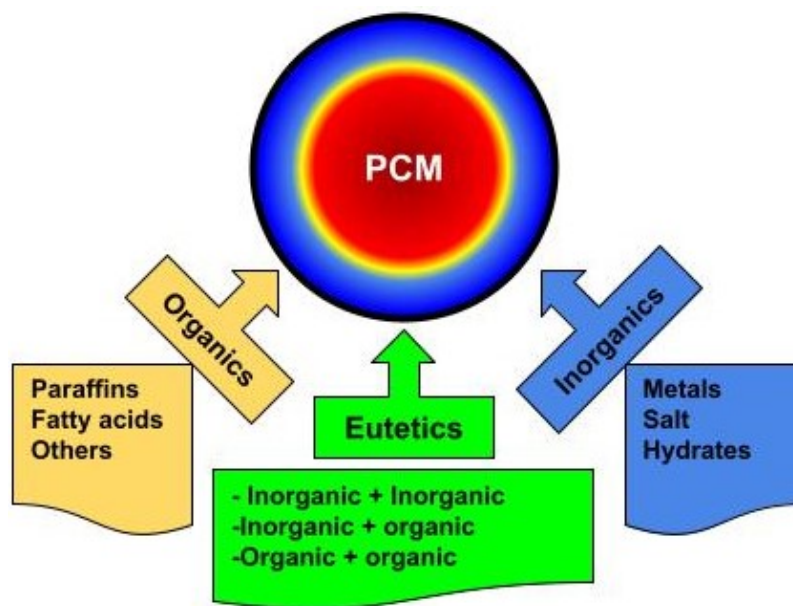
Figure 10 - Energy content x temperature - thermodynamic behavior of PCMs



Source: Author (2023)

There are several chemical substances used as PCMs, the organic ones, inorganic substances and those considered eutectic as summarized in the diagram in Figure 11, where there is a mixture of organic and inorganic substances in different forms, the most commonly used ones being the following (LU, LI, *et al.*, 2017, VELMURUGAN, KUMARASAMY, *et al.*, 2021):

Figure 11 - Different chemical categories of PCMs



Source: Author (2023)

Paraffin Wax: widely used PCM due to its relatively low cost and the availability of different melting points. It can be employed in a variety of applications, including thermal energy storage and climate control systems.

Salt Hydrates: salts combined with water and are known for their high heat storage capacity. Common salt hydrates include sodium sulfate decahydrate and magnesium sulfate heptahydrate.

Organic Materials: certain organic compounds can also act as PCMs. They can have various melting points and are used in applications like building insulation and passive solar heating systems.

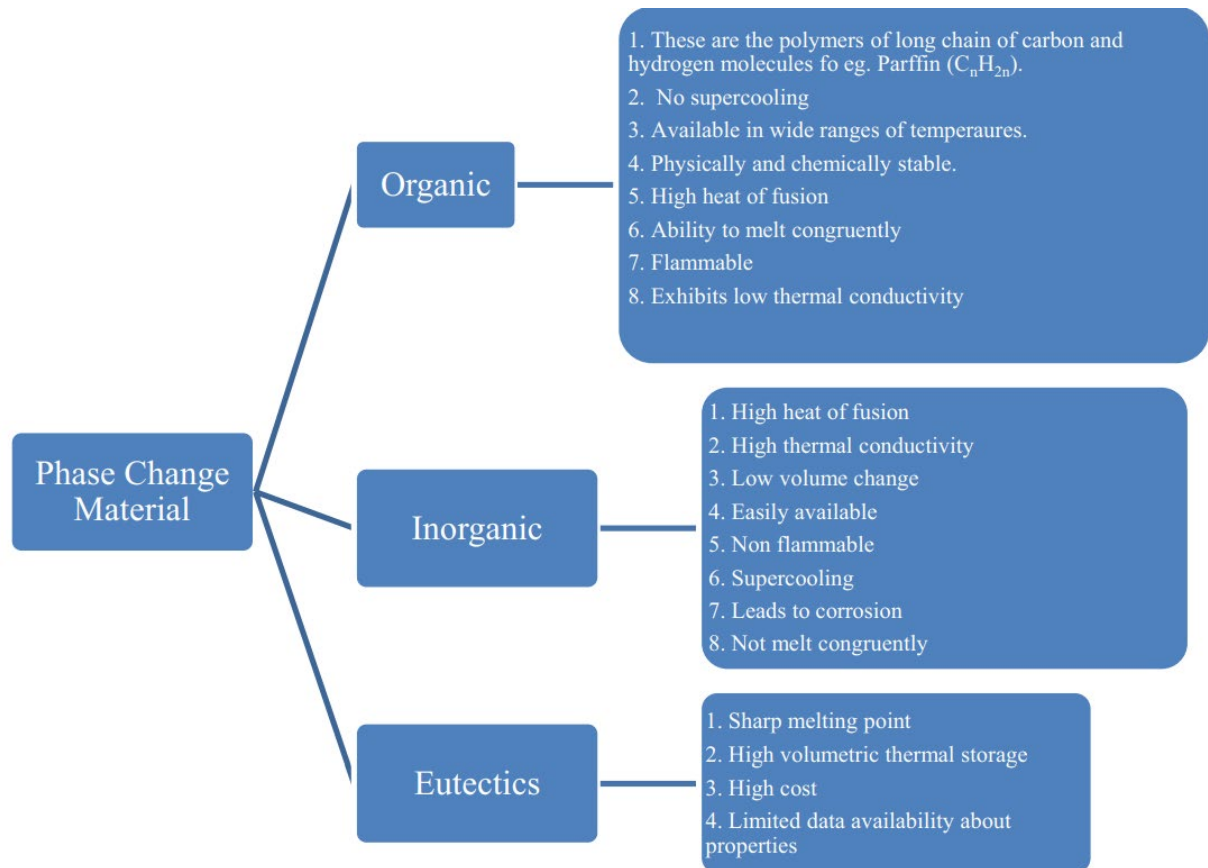
Eutectic Mixtures: these are mixtures of two or more substances that have a lower melting point than any of their individual components. Eutectic mixtures can be designed to meet specific temperature requirements.

Metal Alloys: some metal alloys, such as aluminum-silicon (Al-Si) and copper-indium (Cu-In), are used as PCMs in high-temperature applications.

Bio-based PCMs: researchers have been exploring bio-based materials, like fatty acids and sugar alcohols, for use as PCMs. These materials are renewable and environmentally friendly.

The choice of PCM depends on the specific application and the required melting temperature, heat storage capacity, and other properties as detailed in figure 12. Different PCMs are suitable for different temperature ranges and purposes, and their selection is a critical aspect of designing an efficient thermal energy storage system.

Figure 12 - Properties of different PCM types.



Source: (RATHORE, SHUKLA, 2019)

1.3.2.1. Thermal energy storage

The characteristics of the PCMs mentioned above, therefore, demonstrate that the phase change process allows for the Thermal Energy Storage (TES,) not only through thermochemical methods (chemical reactions) but also through physical methods, such as sensible heat, and in this specific case, latent heat (DE BOER, 2014, DE BOER, SMEDING, *et al.*, 2014, DE GRACIA, CABEZA, 2015, LIZANA MORAL, CHACARTEGUI, *et al.*, 2017). At Figure 13, we can observe the three main mentioned processes for thermal energy storage as explained bellow:

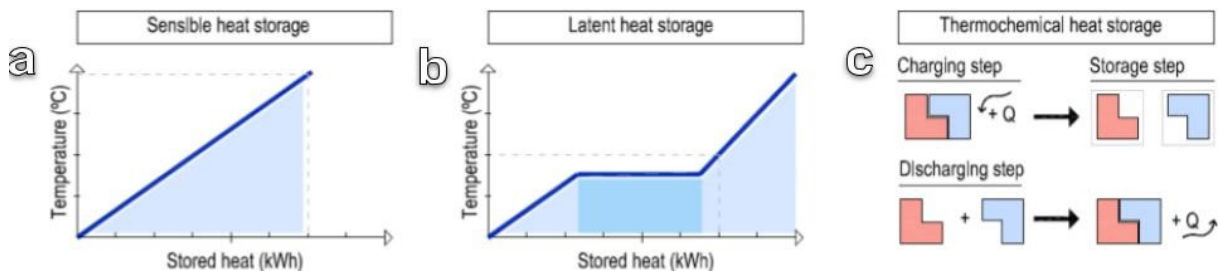
1. Sensible Heat Storage (fig 12a): where thermal energy is stored or released as the material's temperature changes without a change in phase. This occurs when the temperature of

a material increases or decreases, such as in hot water systems or radiators. However, this method is not as efficient as latent heat storage since it requires large temperature variations to store a significant amount of energy.

2. Latent Heat Storage (fig 12b): associated with the use of phase change materials (PCMs). Thermal energy is stored or released during phase changes, such as melting (solid to liquid) or solidification (liquid to solid). PCMs have the capacity to store a significant amount of energy within a narrow temperature range, making them ideal for applications where precise temperature control is essential.

3. Thermochemical Heat Storage (fig 12c): where thermal energy is stored through reversible chemical reactions. These reactions can occur at different temperature ranges, allowing the storage of thermal energy in chemical systems. However, thermochemical systems are often more complex to design and operate.

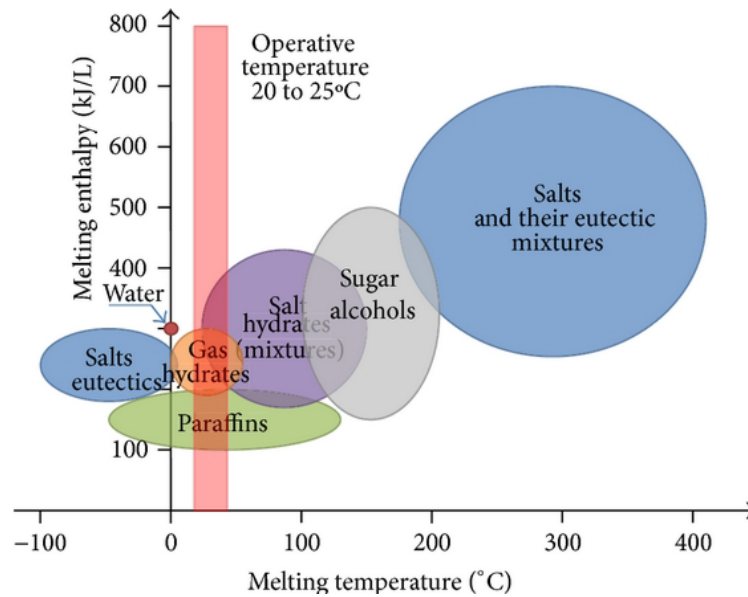
Figure 13 - Scheme representing three thermal energy storage processes. (a) sensible heat, (b) latent heat and (c) thermochemical reaction



Source: (LIZANA MORAL, CHACARTEGUI, *et al.*, 2017) **Adapted by the author (2023)**

Taking into account what was stated above, the use of PCMs has emerged as an effective solution for thermal energy storage, especially in applications that require temperature control and energy density. They play a vital role in energy efficiency and reducing energy consumption in heating, cooling, and thermal energy management systems. Each substance naturally, depending on its chemical composition, has specific state change temperatures and a specific storage capacity, as shown in Figure 14 (VÁZ SÁ, ALMEIDA, *et al.*, 2014), defined by enthalpy (SÁ, 2012, WI, CHANG, *et al.*, 2020), and these characteristics will determine its applicability.

Figure 14 - Melting temperatures and phase change enthalpy for existing PCMs



Source: (VÁZ SÁ, ALMEIDA, *et al.*, 2014)

1.3.2.2. Use of PCMs in construction industry

Constructive enclosures in all planes, whether vertical or horizontal, roofs or walls, are the building elements most evidently feasible for harnessing the energy efficiency resulting from the use of PCM and significant potential lies in the possibility of harnessing thermal efficiency through Latent Heat or Thermal Energy Storage (LHS).

There are buildings with various uses, and the use of PCM as an energy efficiency agent depends on the specific temperature at which one wants to create storage or anchoring. This temperature must naturally be regulated with the material's phase change.

There are important properties that define the selection of PCMs for application in the construction industry (OSTERMAN, TYAGI, *et al.*, 2012). In Table 1 a summary of the relevant properties of PCMs for use in buildings is shown. The main thermal properties include the range of phase change temperatures suitable for the existing conditions, high enthalpy, suggesting a greater amount of possible energy to be stored, adequate thermal conductivity in various phases of use (solid, liquid, or gaseous), specific heat, and high volumetric mass (TYAGI, BUDDHI, 2007).

Physical properties are also relevant, primarily considering the volume change during the phase change. Variation in volumetric mass and consequent liquid or vapor pressure during the phase change can cause the rupture of encapsulations used to seal the substance in its various states.

Of course, PCMs for proper use in the construction industry must also have their chemical properties, such as stability, reversibility of fusion-solidification cycles, durability after multiple phase change cycles, and non-flammability, toxicity, or environmental pollution.

Other factors to be considered include kinetic properties such as nucleation and crystallization rate, but mainly viscosity and the material's ability to flow in its typical states.

Logically, to make the use of the material viable, it is strongly desirable that it is preferably low-cost, abundant and locally available.

Table 1 - Summary table of the relevant properties of PCMs for use in buildings (AKEIBER, NEJAT, *et al.*, 2016, EL-SAYED, TALAAT, *et al.*, 2023, TEIXEIRA, 2019). **Adapted by the author (2023)**

Relevant properties in the selection of PCM to be applied in construction					
Physical	Thermodynamic	Kinetic	Chemical	Environmental	/ Socioeconomical
Reduced variation in density	Melting/solidifying temperature suitable for use	No overcooling	Chemical stability, non-reactive or corrosive	Biodegradability	
Uniform phase change in solid/liquid and liquid/solid passage	High Enthalpy	Viscosity, fluidity or flow capacity	Reversibility in the passage solid/liquid liquid/solid	Durable (does not show degradation after several melting / solidification cycles (Live cycle quality)	
Reduced vapor pressure during phase change	High thermal conductivity (in solid and liquid phases)	Sufficient nucleation and crystallization rate	Non-flammable Non-polluting Non-toxic	Economically accessible	
Reduced volume change upon phase change	High specific heat and high density			Locally and large-scale availability	

1.3.2.3. Challenges in using PCM

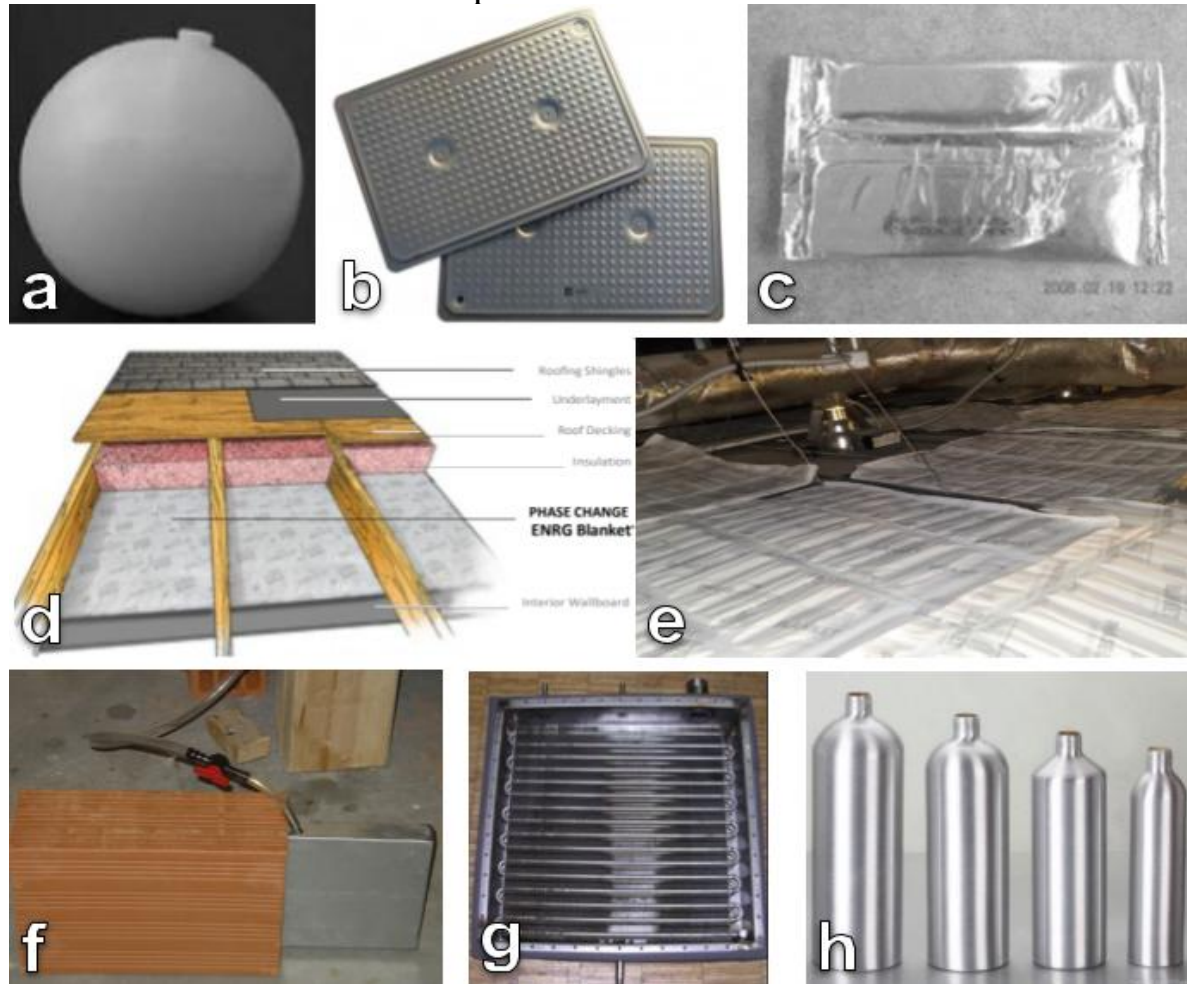
The main challenge in using PCMs for construction industry lies in the need for a change of state to achieve the material's energy operation efficiency. This indicates the necessity of

containing these materials in their solid state as well as in fluid states like liquid and gas if this depending on which transformation the focus is aiming for.

This observation highlights that to use these materials, there must be containers or reservoirs for the substances in various states depending on the temperature they are exposed to, in order to prevent loss (RATHORE, SHUKLA, 2019) .

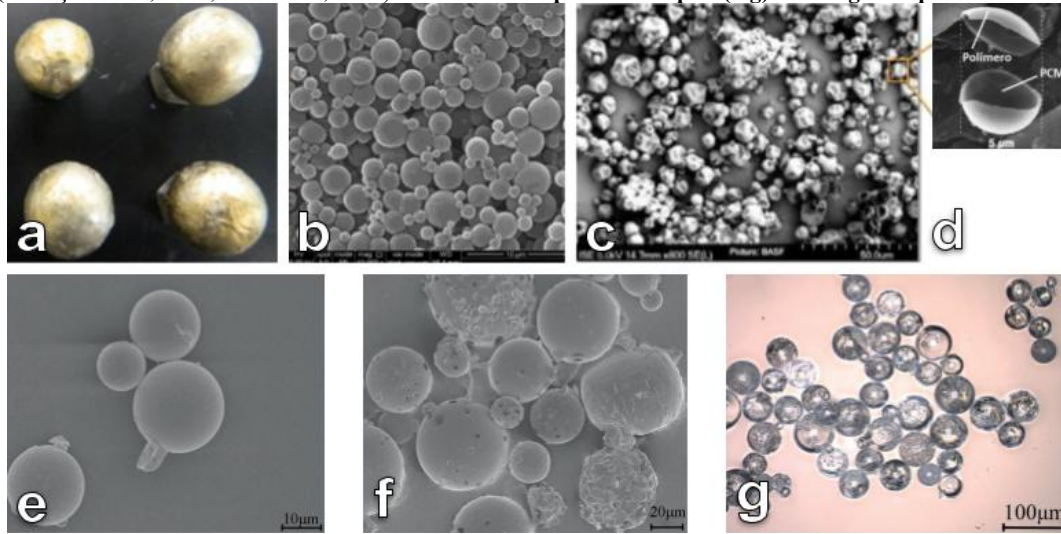
As receptacles for PCMs, various possibilities have been used, especially in macro-scale containers (Figure 15). Encapsulations performed by other polymeric materials, ceramics, among others, have also been studied, both in micro and nano-scale as shown in Figure 16. Physical, physicochemical, and chemical methods are used for these encapsulations, and the main conditions evaluated are strategies against sealing defects in the face of the expansive and fluid properties of PCMs. Additionally, the thermal properties of these encapsulating materials must be taken into consideration to ensure that thermal efficiency is not compromised (HEKMAT, HAGHANI, *et al.*, 2022, KARTHIKEYAN, RAVIKUMAR SOLOMON, *et al.*, 2014, RATHORE, SHUKLA, 2019, SALUNKHE, SHEMBEKAR, 2012).

Figure 15 - Plastic macrocapsules with spherical shape (a); aluminum-coated panel-shaped macrocapsules (b); bag-shaped macrocapsules coated with plastic combined with a metal layer (c). Framed Ceilings scheme (d) and Roofs (e) with PCM blanket PCM. Brick PCM microcapsule filling (f). Photo of the PCM store with immersed heat exchanger. Macrocapsules made in aluminum bottles.



Source:(TRISTÃO, 2014). (PHASE CHANGE SOLUTIONS, 2023). (VICENTE, SILVA, 2014). (STREICHER, SCHULTZ, *et al.*, 2007). (GONÇALVES, 2015).

Figure 16 – (a) Microencapsulation in metal spheres. Paraffin microcapsules (b) encapsulated by melamine resin. Microcapsules for PCM in spherical polymer general aspect (c) and enlargement of a spherical unit (d)(GONÇALVES, 2015, TRISTÃO, 2014). Other microcapsules examples (e-g) with regular spherical structure.



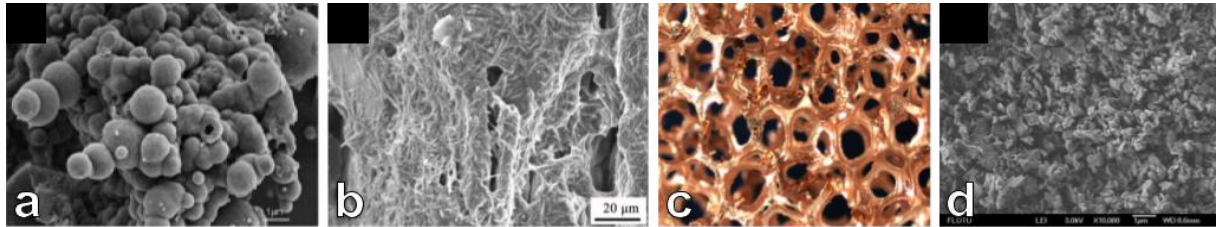
Source: (ALAM, DHAU, *et al.*, 2015), (LIU, Chenzhen, MA, *et al.*, 2017). (GONÇALVES, 2015, TRISTÃO, 2014). (PENG, DOU, *et al.*, 2020).

(ALAM, DHAU, *et al.*, 2015, GONÇALVES, 2015, LIU, Chenzhen, MA, *et al.*, 2017, PENG, DOU, *et al.*, 2020, TRISTÃO, 2014)

1.3.2.4. Porous materials and impregnation

Numerous research studies have been conducted using reservoirs that store PCMs for utilization in building elements and harnessing the resulting thermal efficiency (HUANG, Xiubing, CHEN, *et al.*, 2019). Various shapes and materials have been employed and tested, and materials that offer the possibility of storage through saturation within their natural porosity have not been overlooked. These materials can synergistically contribute to the final product's quality by enhancing physical and mechanical strength, thermal conductivity, chemical stability, among other factors. Expanded graphite, metallic sponges, and aerogels are examples of elements that can be used for this purpose as exemplified in Figure 17.

Figure 17 - MXene nanosheets coated conjugated microporous polymers hollow microspheres incorporating with PCM (a) (ZHOU, YANG, *et al.*, 2024). Polyethylene glycol/expanded vermiculite shape-stabilized PCM composite with silver nanowire (b) (DENG, LI, *et al.*, 2016). Paraffin/metal foam PCM composite (c) (XIAO, ZHANG, *et al.*, 2013). expanded graphite PCM composite (d) (WU, WANG, 2015).



Source: (DENG, LI, *et al.*, 2016, WU, WANG, 2015, XIAO, ZHANG, *et al.*, 2013, ZHOU, YANG, *et al.*, 2024)

Lignocellulosic materials derived from the biomass of secondary xylem plant tissue, such as wood, and, in the specific case of this investigation and focus, primary xylem plant tissue from various bamboo species, possess natural porosity due to their anatomical structure (Figure 18). As this study aims to demonstrate, they can be utilized as a repository for PCM storage. The Table 2 provides values that give an indication of the magnitude of porosity for some of the mentioned materials to assist in comparison.

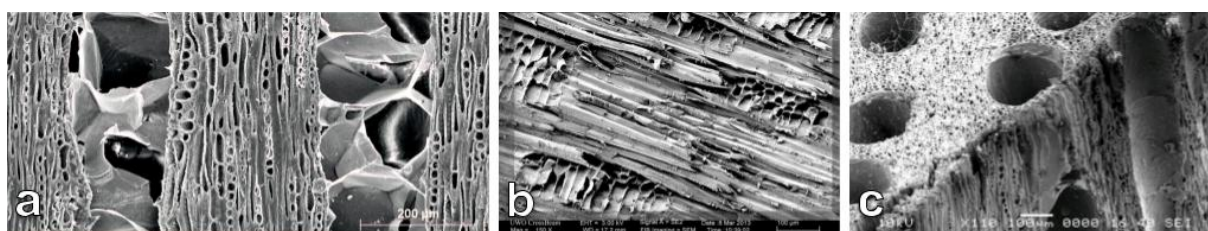
Table 2 - Porosity values in some materials (HUANG, Puxi, CHANG, *et al.*, 2017, KUHN, 2023).

Porosity and density of some porous materials		
Materials	Porosity (%)	Density (g/cm ³)
Aluminum sponge	65-70	0.8-0.94
Nickel Sponge	90-97	-
<i>Quercus rubra</i> Oak Wood	55	0.59
<i>Thuja occidentalis</i> Tuia wood	68	0.36
<i>Phyllostachys edulis</i> Mosso bamboo culm	44-59	-

The empty spaces within lignocellulosic materials are voids that can naturally contain gases or liquids, while the structural part is solid, mainly composed of hemicellulose, cellulose, and lignin (SUN, WANG, *et al.*, 2023). This volume of empty spaces, or porosity, refers to the ratio of the void volume to the total volume. Density, thermal conductivity, specific heat, and moisture content are interrelated properties that have an impact on heat and moisture transfer and the thermal performance of porous materials (CAN, LEE, *et al.*, 2023, CHEN, Yan, HE, *et al.*, 2023).

Wooden constituents' cellulose fibers have the function of forming a skeleton and create a hierarchically anisotropic porous structure with lignin filling and some studies have been undertaken to make better use of this. In (LIN, QIU, *et al.*, 2023) for example, after the removal of lignin and hemicellulose, delignified wood exhibited greater porosity, which is beneficial for encapsulating other functional materials, and it was used as a stable support to prepare wood-based PCMs, encapsulating liquid-solid PCMs (SUN, WANG, *et al.*, 2023). Wood exhibits a complex pore structure, ranging from micro- to macroscales, as shown in Figure 18 - (a) Vessels of *Quercus petraea* wooden species with tyloses. (b) Scanning electron microscope image (SEM) of Toona Mahogany wood (*Toona Ciliata*) and (c) vessel elements in oak. Figure 18 and some comprehensive investigations (SPARAVIGNA, 2023) employed several methods to measure the porosity of both softwood and hardwood tissues. Their research revealed significant variations in bulk density, specific surface area, and porosity (DUK SUH, NAM, *et al.*, 2023).

Figure 18 - (a) Vessels of *Quercus petraea* wooden species with tyloses. (b) Scanning electron microscope image (SEM) of Toona Mahogany wood (*Toona Ciliata*) and (c) vessel elements in oak.

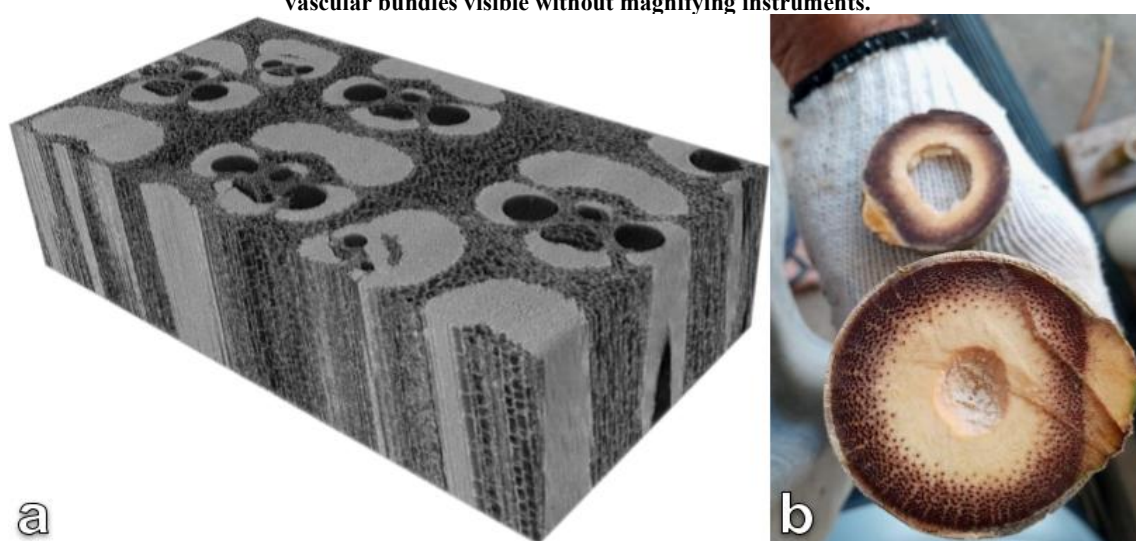


Source:(SPARAVIGNA, 2023)

Going specifically into the topic of this research, when it comes to the porosity of bamboo species it is still in its early stages compared to similar research on timber. When studying the micro-anatomical structure of bamboo, it can be predominantly classified quite similar to wood as a porous composite of long cellulose fibers reinforced with a matrix of lignin and polymeric hemicellulose (WEGST, ASHBY, 2004). Given this fact, it can be deduced that its behavior

regarding PCM impregnation is similar to other materials with equivalent structural composition. The microstructure of different bamboo species, much like in other plant families, is quite similar and richly abundant in vascular bundles (LIESE, 1998), which is also an important factor. In Figure 19 it is possible to observe an enlarged three-dimensional section of the anatomical structure of the bamboo culm with all its apparent roughness and also a photograph where the vascularization is still visible without the use of magnification instruments.

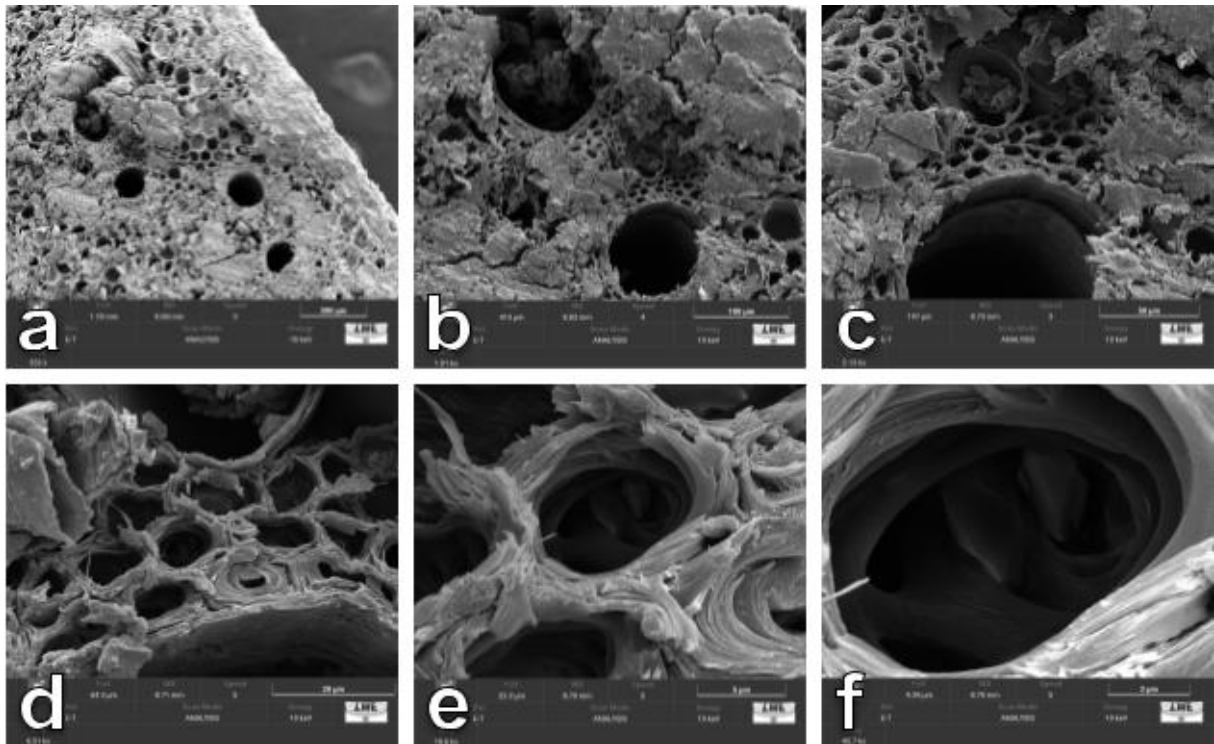
Figure 19 - (a) Three-dimensional image of a sample of plant tissue from *Dendrocalamus giganteus* bamboo culm in its 3 cutting planes: tangential, radial and longitudinal. (b) Transverse section of *Bambusa tuldoidea* culm showing the vascular bundles visible without magnifying instruments.



Source: (a) (KRAUSE, DE ANDRADE SILVA, *et al.*, 2016) (b) Author (2023)

Just as in the woody tissue, the porosity of bamboo depends on its existing empty spaces in vascularization, intracellular and intercellular regions, and cell walls (BARNETT, JERONIMIDIS, 2003, MORESCHI, 2005) and similarly to moisture, the expectation of this investigation was that the PCM in its liquid state, when impregnated into the constitutive tissue of previously dried bamboo, occupies significant portion of these voids (illustrated with amplified images from the Figure 20), taking into consideration the differentiated chemical composition with its specific properties (DRUMOND, WIEDMAN, 2017, IDRC CRDI, 1988).

Figure 20 – Sequential images (a-f) extracted from Scanning Electron Microscopy (SEM) of *Phyllostachys aurea* bamboo culm, progressively increasing in magnitude, demonstrating the extremely high surface roughness of the longitudinal cut as well as the vessels and conducting bundles, in addition to the fibers and the voids of their lumens.

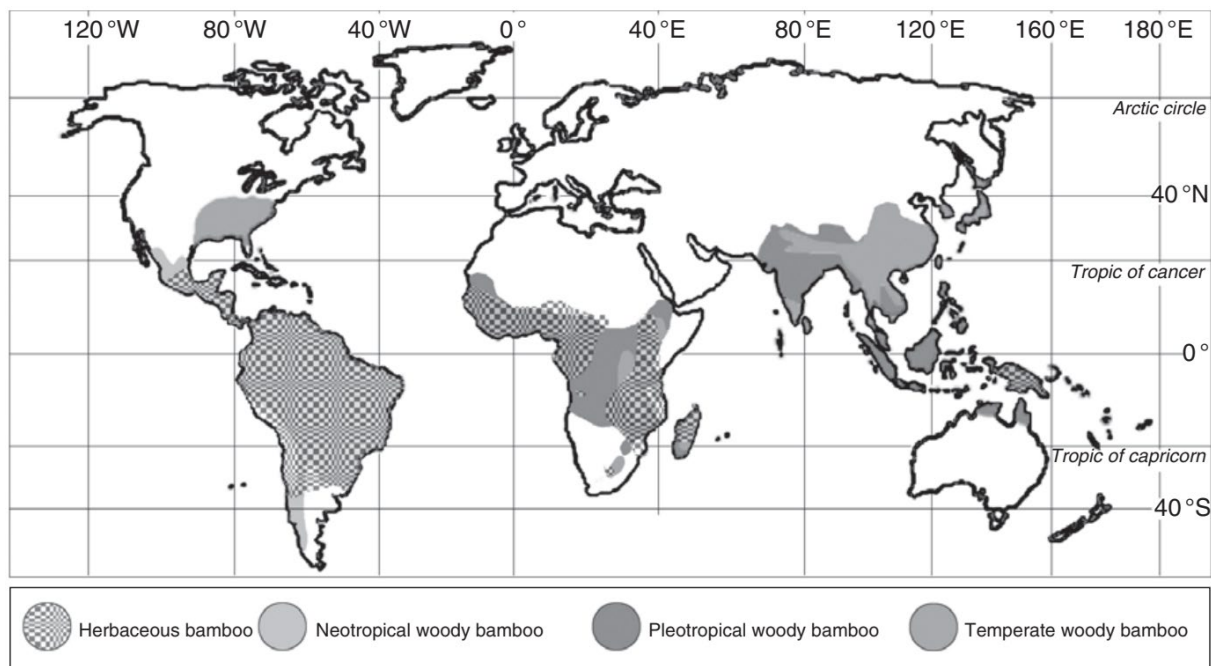


Source: Author (2023)

1.3.3. Bamboo as a construction material

Bamboo has historically been used by humanity as a material for various purposes, and our ancestors did not overlook the qualities that allow this plant to be used for multiple applications, including as a construction material (VAN LENGEN, 2021).

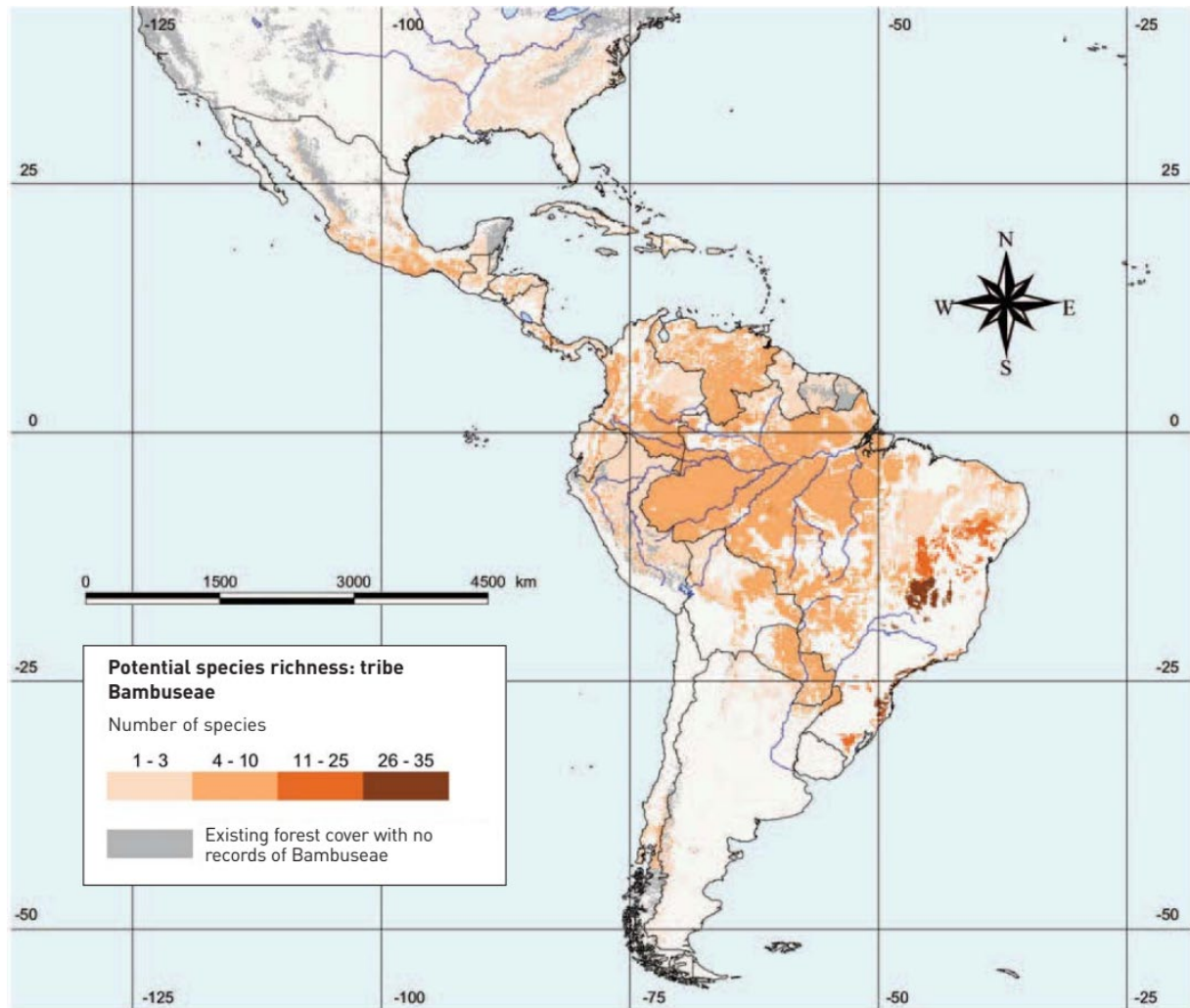
Figure 21 - World distribution of woody and herbaceous bamboos.



Source:(DAS, BHATTACHARYA, *et al.*, 2008)

According to botanical taxonomy, bamboo belongs to the family of grasses, subfamily Bambusoideae, which comprises about 1575 species (BYSTRIAKOVA, KAPOV, *et al.*, 2004). It is mainly found in tropical and subtropical regions with high humidity (as shown in Figure 21 - World distribution of woody and herbaceous bamboos. Figure 21), and there is a significant variety, some of which have not yet been studied in Brazilian territory (SILVA, Frederico Rosalino da, 2019). The Americas, as a whole, boast a significantly greater abundance of bamboo species compared to continental Africa or Madagascar. However, when considering bamboo diversity, the Americas exhibit fewer varieties than the Asia-Pacific region (Figure 22). In Brazil, there are 134 naturally occurring species (TAKAHASHI, 2006), but there is also a significant presence of various common exotic species due to their historical use as utilitarian plants, primarily from the East.

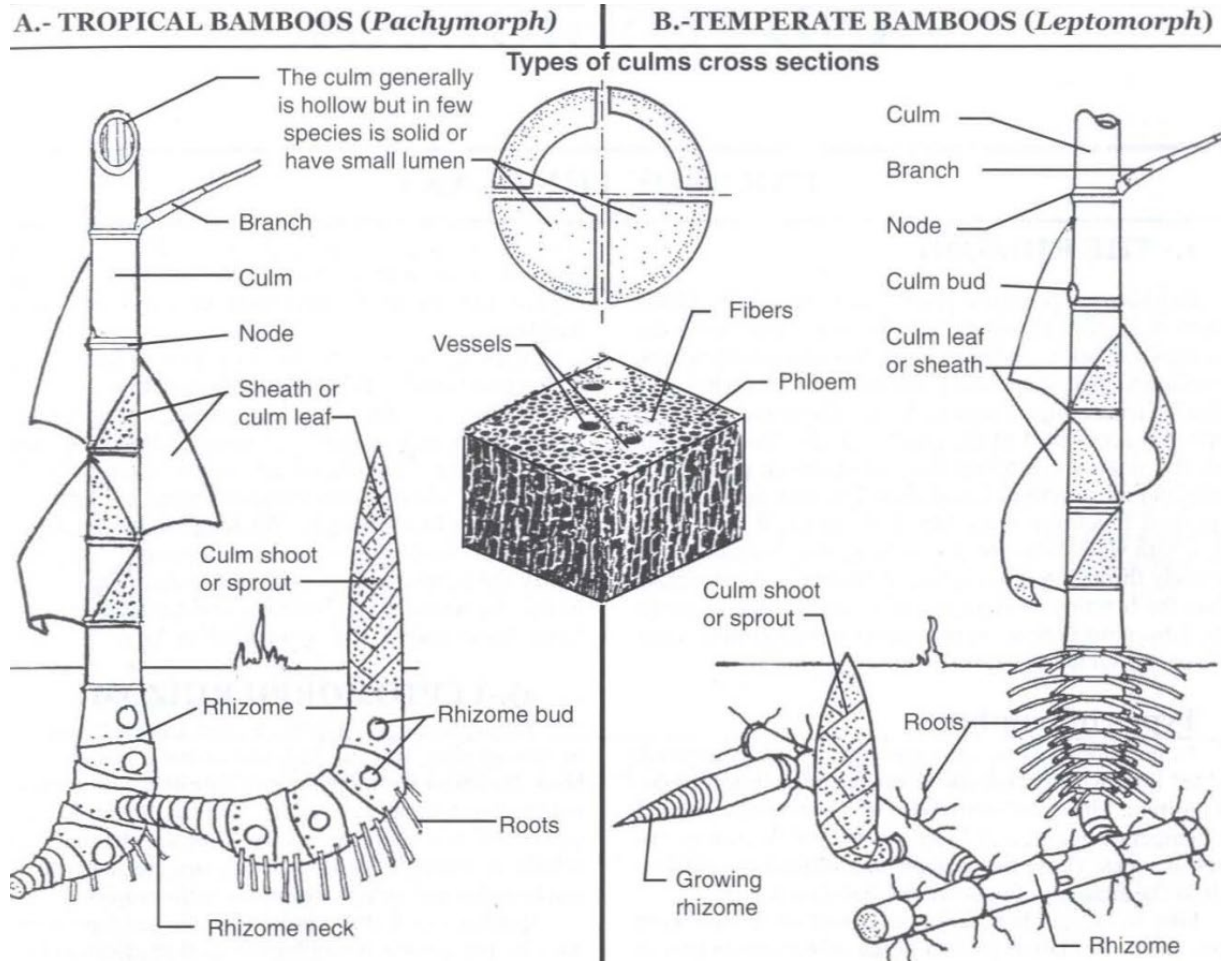
Figure 22 - Map of potential species richness of woody bamboos in the Americas.



Source: (BYSTRIAKOVA, KAPOŠ, *et al.*, 2004)

Bamboo species commonly found in tropical regions are considered pachymorphs and have clumping characteristics in their forest individuals. On the other hand, bamboo species originating from temperate climates predominantly have a running growth habits and its main macro anatomical characteristics can be seen in Figure 23 (HIDALGO-LOPEZ OSCAR, 2003).

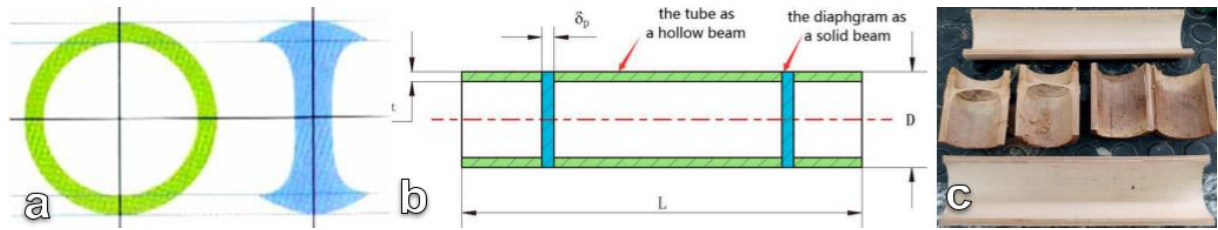
Figure 23 - Bamboos from tropical and temperate zones.



Source: (HIDALGO-LOPEZ OSCAR, 2003)

A common morphological characteristic of the most common bamboo species are their nearly cylindrical, hollow shape with a succession of nodes and internodes (Figure 24), which provides them with a very high level of natural structural efficiency and is the main reason for their superior physical and mechanical strength when compared to other materials, making them suitable for various construction purposes (KRAUSE, DE ANDRADE SILVA, *et al.*, 2016, WEGST, ASHBY, 2004) and widely recognized for having the highest specific energy absorption and specific stiffness among natural materials (ZHANG, Taochuan, DUAN, *et al.*, 2020).

Figure 24 – (a) Efficient natural structural design: bamboo longitudinal and cross sections. (b) Bionic design of a bamboo inspired tube–diaphragm coupling beam with its structural parameters. (c) Morphology of the culm of *Phyllostachys aurea* demonstrating the node diaphragms and the cylindrical cavity of the internodes.



Source:(VAN, 2006, ZHANG, Taochuan, DUAN, *et al.*, 2020) and author (2023)

It is essential to emphasize the diversity of uses that bamboo species have in everyday rural life, particularly as crucial support for communities and small-scale agriculture throughout their production chain (NISHIMURA, 2004, REUBENS, BREZET, *et al.*, 2010), including food consumption, the production of various objects, as well as their use for charcoal and firewood. This reinforces the sustainability aspect of bamboo in environmental and socio-economic terms (PRIETO, VIDAL, *et al.*, 2013). The bamboo production chain and its diversified uses in the different stages and levels of production and manufacturing are illustrated in **Erro! Fonte de referência não encontrada..**

Figure 25 - Sustainable character in the socioeconomic aspects of the bamboo production chain and its diversified uses in the different stages and levels of production and manufacturing.



Source: (CENTER, 2023, CORRÊA, NEMATENC, 2023, FOODRECIPES, 2020, HABIT, 2022, INDICUS, 2023, MULHER, 2023, SUZUKI, ACAYABA, 2020, VIVO, 2023) **Edited by Author (2023)**

Another notable aspect is the vulnerability of bamboo in terms of durability when exposed to weather conditions and wood-destroying organisms (KAUR, SATYA, *et al.*, 2016, KUMAR, Satish, SHUKLA, *et al.*, 1994, MOHAN, DASH, *et al.*, 2022). Therefore, it is highly advisable to use treatments to enhance its durability when used for various purposes. In construction, there are various forms of application, from using whole bamboo culms with minimal processing to using open and planed culms in the form of mats or split into slats, and even engineered forms such as laminated bamboo boards and other types of composites (HIDALGO-LOPEZ OSCAR, 2003).

Bamboo finds various applications in construction, including reinforcing foundations, as well as in a wide range of structural possibilities such as beams or two- and three-dimensional

trusses (**Erro! Fonte de referência não encontrada.**). It's also used for wall cladding and flooring, and can even be used for roofing in various forms (FONTENELLE, 2006).

Figure 26 - Bamboo in various construction uses such as: (a) scaffolding, (b) structural trusses, (c) covered bridges, and (d) complex three-dimensional bundle structures.



Source: (ALEJANDRO MÉNDEZ QUINTERO, PATRICIA TAKEUCHI TAM, *et al.*, 2022, BUILDINGS, 2023, CORRÊA, NEMATENC, 2023, NEWS, 2023).

1.3.3.1. The use of bamboo as a building envelope material

Despite its vulnerability when exposed to the elements, bamboo has been used as a material for constructing walls and roofs in buildings since ancient times, especially in the East and in regions of the Americas where this species is abundantly found (AKINLABI, ANANE-FENIN, *et al.*, 2017).

The most common use of bamboo in building enclosures is for walls, partitions, or cladding (TAKAHASHI, 2006). Buildings constructed with bamboo structures often employ frame techniques to interlock different planes. In these cases, the main upright elements of a bamboo wall (studs and beams) are typically integrated into the overall building structure, as seen in the bahareque technique (historically used in regions of Colombia) (HIDALGO-LOPEZ OSCAR, 2003). Bamboo-based enclosures or walls can take various forms, including round culms, half-round culms, slats, woven mats, or “esterillas” (flat bamboo board), and more recently in the form of cross-laminated glued laminates. The use of bamboo for windows and doors is also common as seen in Figure 27.

Figure 27 – (a) External closure in glued bamboo laminates, (b) Stalks with low processing in coating. (c) window and wall made of mat and bamboo culms. (d) construction of a Bahareque wall.



Slatted scale roof (ARCHDAILY, 2023, CONSULTING, 2023, GRIFFITHS, 2014) and (c) Author (2023)

Figure 28 – (a) three-layer bamboo roof shingles. (b) Bamboo culm half-pitched roof. (c) Corrugated bamboo roofing sheets. (d) Slatted scale roof.



Source: (ARMBRUST, 2023, BAMBOO, 2023, BUILDINGS, 2023, CENTER, 2023)

When it comes to roofing, the most simplified and historically common use is the simple half-round cut of the bamboo culm as seen in Figure 28b, with the nodes removed to create tiles that function as cover and channel, much like traditional colonial tiles. There are various other forms of use, such as open and planed culm, and even engineered composites treated industrially, for example. These usage forms have been studied for potential improvements.

1.4. Theoretical Framework concluding remarks

The conceptual path presented in the theoretical framework previously outlined reinforces the importance of conducting studies with the materials selected for this research. The natural characteristics and functional properties demonstrate that, in the current historical context, this is the most appropriate direction for the necessary in-depth research to be undertaken to develop genuinely clean, disseminable and durable technologies.

The review of the topics covered served as the foundation for defining the experimental perspective adopted in the steps presented straight ahead, and the information was essential for defining the procedures carried out.

SECOND PART - PAPERS

ARTICLE 1



12th World Bamboo Congress

Taiwan, 18-22 April, 2024

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Bamboo-PCM: The use of *Phyllostachys aurea* culms as a receptacle for thermal storage through phase change material impregnation

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Abstract

In a quest for sustainability, where the construction industry plays a significant role in environmental impacts, research traces a relevant path seeking the environmental efficiency of buildings through the use of materials from renewable sources, such as bamboo. In climates characterized by high-temperature variations, the incidence of solar radiation and the absorption of heat by building envelopes becomes crucial materials that have advantageous thermal properties contribute to improving environmental comfort by reducing the use of high-consumption active cooling systems. This investigation seeks to unite bamboo's naturally porous lignocellulosic biomass, with its advantageous properties, both in the carbon fixation from the atmosphere and for its physical-mechanical resistance, with the use of phase change material (PCM) and its thermal properties. Culms of the *Phyllostachys aurea* species were utilized as a reservoir for PCM to confer thermal energy storage properties to the resulting object. Thermal variation tests showed that the impregnated bamboo samples effectively reduce temperature fluctuations by tending to anchor it to the PCM's specific change-of-phase temperature. Three different types of bamboo samples were comparatively analyzed: raw culms, culms sealed with polyurethane resin (PU), and impregnated with PCM also sealed with PU. The production process sought economy and minimal processing to facilitate its reproducibility. In terms of anatomical structure, the pores within bamboo culms provided enough space to store the PCM and obtain a high heat storage capacity. The tightness against PCM leakage in its liquid state, provided by the PU seal, ensured that there would be no subsequent loss due to flow. This study demonstrated that PCM-impregnated bamboo culms are promising for building temperature regulation applications.

Keywords: Bamboo, Phase change material; Thermal efficiency, *Phyllostachys aurea*.

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1. Introduction

Bamboo is a renewable natural resource, and a significant reduction in the environmental impacts of the construction industry can be achieved by promoting the use of this material, as it seems to have been tailor-made for use in buildings. This resource's availability, easy dissemination, quick maturation for harvesting, and suitable physical and mechanical properties make it ideal for construction applications as a replacement for more environmentally impactful materials that are derived from non-renewable resources or native forest resources that are exploited without proper management and conservation. On the other hand, cutting-edge research into improving materials' thermal capacity and efficiency has been successfully exploring the potential of Phase Change Materials (PCMs). These materials can store latent energy, and their use in a building can significantly smooth out temperature fluctuations, reducing the need for climate adaptation of spaces to natural climate variations. When a phase change occurs due to a temperature change that prevents the PCM from remaining in its previous state, there is a reorganization of intermolecular chemical bonds. This modification requires energy movement in both endothermic and exothermic directions, depending on the direction of the transition (Sharma et al. 2009). In practice, phase change materials, at their melting or evaporation points, solidification or condensation, continue to absorb or release calories without altering their temperature for a certain period, resulting in a latent heat insertion during this state transition, as observed in Fig. 1 with a central "plateau."

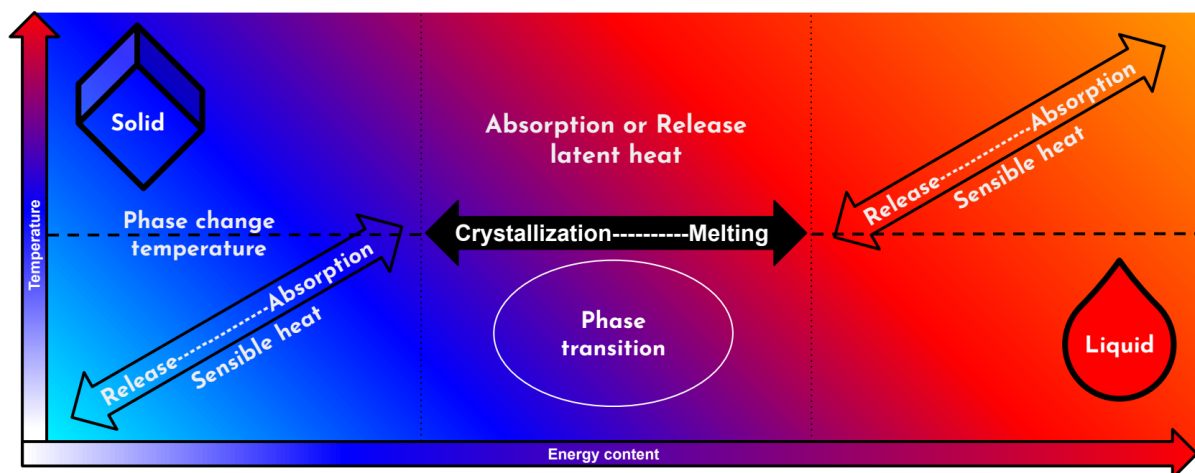


Fig. 1. Energy content x temperature - the behavior of PCMs.

According to (Cabeza et al. 2011), the main advantage of latent heat storage is the high storage density within small temperature ranges, making it suitable for both heating and cooling of buildings. It can be incorporated as a passive system or in active climate control

systems. Various research efforts have sought to identify structures that could serve as receptacles for PCMs to contain these substances in their various physical states, which are essential for their thermal efficiency. Among the various materials used for PCM containment, porous materials have demonstrated interesting capabilities. This current research aims to combine the existing capacities and properties of lignocellulosic materials, such as bamboo, which is naturally porous, with the thermal efficiency induced by the possible impregnation of phase change material into the voids of its anatomical structure.

The bamboo species *Phyllostachys aurea* is abundantly found in Brazilian territory, and is often used for rustic and artisanal purposes in traditional communities. However, it sometimes competes aggressively with local native species (Rios and Farias, 2021; Vasata et al. 2021). Nevertheless, its industrial use or processing for commercially advantageous situations remains incipient. This research seeks to explore another potential benefit that leverages the best characteristics of this material in conjunction with PCM. Therefore, the primary objective of this research is to evaluate the possibility of using the culms of *Phyllostachys aurea* bamboo as a reservoir for PCM within its natural porosity. The resulting object should retain the qualities of bamboo while acquiring the inherent thermal capacity of the PCM in sufficient quantities for its functionality.

2. Materials and methods

The primary material used in the various experimental stages was bamboo culms of the *Phyllostachys aurea* species, commonly known as "Cana da Índia" in Brazil. It was obtained by the author at coordinates UTM Zone 23k: latitude: 7623194.48mS and longitude: 545573.09mE. In Fig. 2, we can observe the clump from which the research material was extracted (A) and the sections of stalks that were already selected, cured, dried, and cut for impregnation (B). This species is an abundant, spreading exotic species in the Brazilian territory, especially in the southeast region. It is widely used in other parts of the world but is relatively underexplored commercially in Brazil. It possesses high physical-mechanical resistance and durability compared to other similar materials (Sánchez Vivas et al. 2019).



Fig. 2. Materials used in the research: (A) Clump of *Phyllostachys aurea* where the research material was harvested, (B) Pieces of bamboo culms used, (C) Commercial CrodaTherm 24 PCM, and (D) Resin used for sealing PU VEGETAL – TYPE "V" commercial.

The phase change material (PCM) used was CrodaTherm 24, a commercial product with a melting temperature of approximately 24°C and a solidification temperature of approximately 21°C. It was obtained through a donation from Croda International Plc (Crodatherm, 2020), as shown in Fig. 2 (C). This PCM has a specific temperature range for phase change that is very close to the ideal thermal comfort temperature for use in buildings. Additionally, a PU Vegetal – Type "V" sealing resin was used, which is a two-component polyurethane waterproofing agent of vegetable origin (derived from castor oil - *Ricinus Communis*), with an amber color (Sinergia, 2020), as depicted in Figure 2 (D). This resin has application and performance characteristics suitable for the sealing, durability, and waterproofing requirements of the research. Its natural origin from a renewable plant resource adds to its appeal. The research methodology essentially involved the following processes: collection and preparation of samples for analysis, essential physical and morphological characterization of the collected bamboo, thermal analysis to confirm the effect of impregnated PCM, macroscopic and microscopic visual examination of the samples, as well as essential chemical characterization.

2.1. Cutting and preparation of stalks and production of essay specimens

Three distinct treatments were considered: raw bambooculm (control group, without any treatment), bamboo culm sealed with PU (referred to as "Analysis 1"), and bamboo culm impregnated with PCM and subsequently sealed with PU (referred to as "Analysis 2"), as summarized in Table 1. These treatments were selected to investigate not only the influence of PCM but also any potential effects, particularly concerning thermal behavior, associated with the application of applying the PU resin.

Table 1. Treatment and denomination of samples used in the thermal test.

<i>Phyllostachys aurea</i>	Objective	Denomination
Raw bamboo culm - without treatment	control	Control
Bamboo culm sealed with PU	analysis1	PU
Bamboo culm impregnated with PCM and sealed with PU	analysis2	PCM

From the bamboo samples collected for the research, those with the most appropriate suitable dimensions for the research objectives were selected. The sections chosen were extracted from the middle third of the bamboo stalk, with both the basal third and the upper third being excluded from consideration and then discarded. All procedures were carried out in accordance with the Brazilian bamboo standard NBR 16828-2 (ABNT 2020). The selection criteria were primarily based on factors such as the relationship between diameter, node spacing, and wall thickness. It is worth noting that the central portion of the bamboo culm is the most resistant to stress (Hidalgo-Lopez Oscar 2003). Additionally, this central region boasts a more uniform morphology characterized by regular node spacing and a cylindrical cross-section. The collected bamboo stalks were subjected to a two-week period of natural drying or curing, ensuring that they were protected from exposure to adverse weather conditions. Following this, they were longitudinally cut to the appropriate dimension of (250 mm, enabling them to fit comfortably into the thermal test chamber for the hotbox essay. These prepared specimens were then placed in an oven for induced drying, following established procedures documented in literature (Forest Products Laboratory (US). The Laboratory, 2010; Moreschi, 2005; Moura, Dalla, Vieira, et al. 2018). The next step involved impregnating the samples using a vacuum pump suction method. Immediately upon completion, they were stored in a refrigerated environment to prevent any potential loss of PCM through melting or leakage. This impregnation process required adapting cut plastic bottles to conform to the irregular shapes of the bamboo stalks, creating vacuum formation, as illustrated in Fig. 3a and 3b. These adapted bottles were then connected to the suction pump hose, as shown in Fig. 3c. It's important to note that the PCM was already in a liquid state due to the ambient temperature exceeding 24°C.

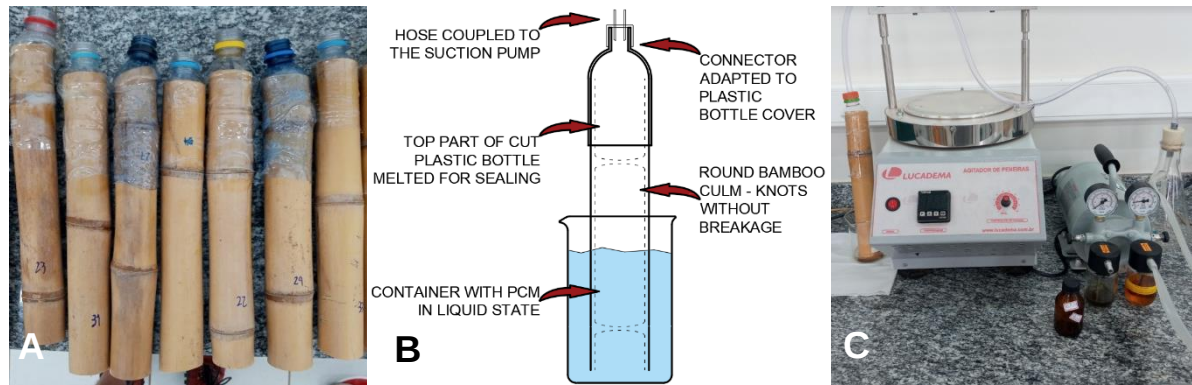


Fig. 3. Used system for impregnating round bamboo culms by vacuum pumping. (A) Culms with plastic bottles adapted at the end for sealing and suction, (B) Diagram of the impregnation scheme, (C) Impregnation setup in operation.

Upon activation of the pump, the formation of bubbles at the upper end of the culm was observed. The completion of saturation was determined by the appearance of an oily substance at this location, indicating the successful filling of the vascular bundles and other porous regions within the stalk. Any surplus PCM on the surface of the stalks was removed using absorbent paper towels after cutting and removing the adapted plastic bottle piece.

Following the impregnation process and allowing the samples to cool (within a freezer at approximately -6°C) for the solidification of the PCM, the specimens, maintaining their cylindrical form with a length of 250mm as illustrated in Fig. 4a, underwent cross-sectioning to create curved strips (Fig. 4b). This process mirrored the model used in tile production (Fig. 4c). To meet the testing criteria, the septa or nodes present in the stalks were also removed using tools such as a chisel and mallet, and the test specimens were labeled for identification.

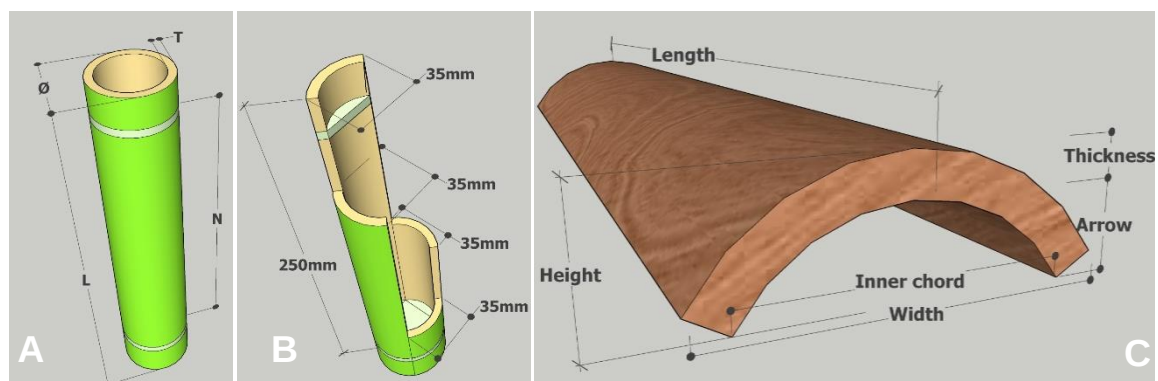


Fig. 4. The original shape of the sample from the impregnation process is depicted in (A), and (B) illustrates the schematic of the longitudinal cut of the stalks followed by the expected final shape (C).

The sealing or coating process was carried out by mixing the components of the PU resin and depositing the test specimens onto a suitable support for manual painting using a common commercial brush (Figure 5). This process demanded swift execution due to the short drying time of the product. The PCM-impregnated samples had to be sealed within the controlled environment of an acclimatization chamber, where controlled humidity and temperature levels were maintained, approximately around 19°C with a relative humidity of 60% in the ambient air.



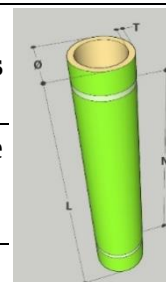
Fig. 5. Two-component PU mixture for application (A) and the systematization for application (B).

2.2. Basic characterization

In order to characterize the samples and establish correlations between observed phenomena and the unique properties of each material, various general aspects were assessed throughout the process, including morphological and anatomical characteristics. The samples were initially treated in their natural cylindrical stalk form for this test, exhibiting the features in Table 2.

Table 2. Morphological characteristics of the samples.

Samples	Culms Average dimensions(mm)		general Average of the nodes		characteristics
	Diameter Ø	Length L	Wall thickness T	Averaged distance Amount N	Averaged distance (mm) N
<i>Phyllostachys aurea</i>	40	250	5	1	190



Moisture content measurements were conducted using an electronic sensor designed for this purpose, the Stanley model STHT77030X. The samples were not weighed at the time of cutting but rather in a laboratory setting after undergoing natural air drying to reach hygroscopic equilibrium (Forest Products Laboratory (US). The Laboratory, 2010; Moura et al. 2018; Zen et al. 2019), and), followed by subsequent resizing.

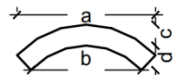
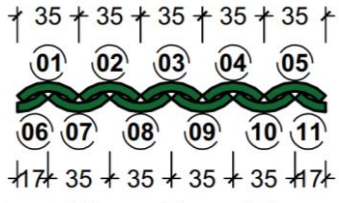
The determination of apparent density was calculated as the ratio between the dry mass (weighed using a precision scale following oven drying) and the water-saturated volume (determined using the displaced liquid method based on Archimedes' principle), while considering the irregular shape of the samples (Forest Products Laboratory (US). Laboratory 2010; Moreschi 2005). The mass measurements were also taken before and after impregnation with PCM and subsequent application of the PU sealing resin, thus enabling the determination of the content of these substances in the final sample.

2.3. Hotbox essay

For the thermal tests, a laboratory-developed thermal box setup was utilized due to the absence of equipment capable of directly measuring the thermal behavior of the samples. This setup was modeled after an instrument designed for measuring thermal insulation capacity, commonly referred to as a "hotbox" (Eugênio 2016; Terra 2018). It involved the use of two 8-liter thermal insulation boxes made of polystyrene (EPS) with an approximately 20 mm thickness of 20mm. These boxes were stacked with an EPS support, which introduced a septum between them, serving as the placement area for the samples to be evaluated, effectively acting as a diaphragm. The objective of the test was to assess the attenuation of thermal load between the two thermally isolated environments with initially equal temperatures.

In essence, one of the boxes was equipped with a heat-emitting element, in this case, an incandescent bulb (glass bulb with a Tungsten filament and E27 non-ferrous socket, with a power of 15 W and a voltage of 127V), referred to as the "active chamber." The other box, termed the "passive chamber," received the heat variation from the active chamber, which was "filtered" or attenuated by the samples, creating a barrier or obstacle between the two environments, as outlined in the scheme presented in Table 3.

Table 3. Morphology, designation, organization, and dimensions of the samples.

Cross-sectional diagram and sample organization.	
Averaged dimensions(mm)	
	a= 35mm b= 25mm c= 05mm d= 07mm

Phyllostachys aurea

To ensure accurate temperature measurements, eight type K thermocouples were employed in a data collection system with temperature measurement and recording capabilities, boasting an accuracy of four decimal places in °C. Temperature readings were periodically recorded at predefined time intervals using software provided by the manufacturer of the commercial equipment, the Pico Technology USB TC-08 thermocouple data logger with PicoLog data logging software.

To enhance the setup's reliability, a layer of commercial aluminized foil was applied to the surface of the active chamber's box as a coating (Figure 6b). This measure was taken to prevent overheating caused by the light bulb from damaging the EPS box wall. Additionally, within the sample placement area, an EPS-made barrier was embedded (Figure 6a) to securely hold the test specimens and prevent any gaps that might allow air passage between the chambers. Given that the samples are irregular materials without precise packaging, ensuring a snug fit was crucial to eliminate gaps or openings.

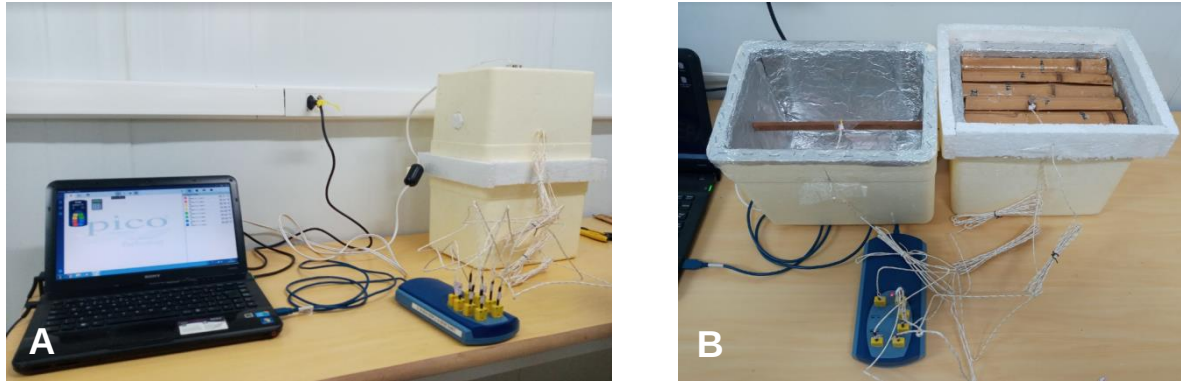


Fig. 6. (A) The Hotbox essay setup in operation and the arrangement of samples and thermocouples in the thermal box (B).

The thermocouples in the thermal box system were positioned at four levels, with duplicates, to guarantee the reliability of the collected data. These thermocouples were arranged as follows:

- External Air Thermocouple: Positioned at the geometric center of the active chamber's volume.
- Thermocouple on the External Surface of the Sample: Placed on the surface exposed to the environment of the active chamber of the evaluated barrier.
- Thermocouple on the Internal Surface of the Sample: Placed on the surface exposed to the environment of the passive chamber of the evaluated barrier.
- Internal Air Thermocouple: Positioned at the geometric center of the volume of the passive chamber, as illustrated in Fig. 7.

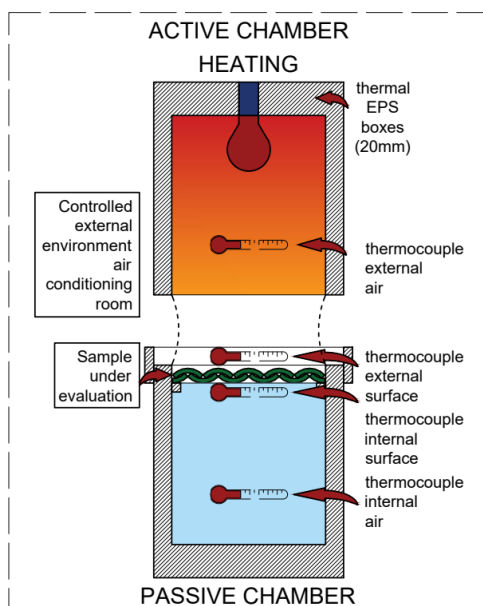


Fig. 7. Schematic diagram of the Hotbox setup with the location of the thermocouples.

To conduct the experiment, it was important to note that the PCM used had a melting temperature of approximately 24°C, and the heat storage process and the phenomenon under investigation occurred within this temperature range. Consequently, the experiment was planned to allow the temperature to traverse this range with a substantial safety margin both above and below this value. This was necessary to observe the phenomenon in both its heating and cooling phases. The experimental procedure commenced with the organization of the thermometers and parameters in the application to ensure accurate data recording (data collection frequency, designations, etc.). Subsequently, the incandescent lamp was activated, initiating the temperature increase in the system, referred to as "Phase 1." The room where the experiment was conducted was climate-controlled at a temperature of approximately 19°C, significantly below the PCM's melting point. Therefore, the active box setup needed to elevate the temperature above 24°C but not significantly beyond 40°C to avoid a substantial deviation from the ambient climate. This choice determined the power of the heating element. Phase 1 of the experiment, focused on temperature increase, commenced with the activation of the lamp when the system was at a temperature of around 19°C. The temperature in the active chamber was raised to values exceeding 40°C, and then the temperature increment gradually decreased, as observed by the thermocouples in both the active and passive chambers. This indicated the stabilization of the system with the energy source activated, a process that took approximately 90 minutes. To initiate Phase 2 of the experiment, involving temperature decrease, the active chamber, which contributed heat, was turned off and separated from the passive chamber. This allowed for the observation of a rapid temperature reduction to ambient temperature. Gradually, the influence of the barrier/sample on this cooling process was also noted. This temperature reduction and stabilization process took approximately 40 minutes.

2.4. Visual analysis and chemical characterization

Visual analyses were employed to facilitate the anatomical examination of bamboo plant structures, allowing for the observation of tissue patterns, vascular structures, and porosity. To inspect internodal regions, light optical microscopy was used to observe internodal regions, and cross-sectional cuts to capture images of the stalks. These samples, measuring approximately 10 mm x 5 mm x 5 mm, were derived from bamboo strips and placed in molds for embedding. Subsequently, the blocks underwent vacuum impregnation with embedding epoxy resin (Epofix) from the Struers brand. The blocks were sanded using a sequence of

progressively finer grits on an orbital sander and subsequently polished with diamond paste on an orbital polisher. This procedure was carried out at the Centro de Tecnologia Mineral (CETEM) (Krause, 2015; Krause et al. 2016).

For thermal analysis through thermogravimetry (TGA), which aimed to confirm the chemical composition of the samples, a TGA Q500 TA Instruments thermal analyzer (Delaware, USA) was used, set with a heating rate of 10°C/min. Between 7 and 10 mg of powdered sample were placed in the crucible and heated from 25 to 600°C. The analysis conditions included a synthetic air atmosphere (80% N₂ and 20% O₂) flowing at a rate of 60 mL/min, with a heating rate of 10°C/min (Raabe et al. 2015). Critical temperatures for mass loss, including the initial temperature, the temperature range within which losses between 70% and 80% of the sample mass occurred (shoulder temperature), and the temperature at which the final mass stabilized (final temperature), were determined through examination of the TG and derivative TG curves. Fourier-transform infrared spectroscopy (FTIR), vibrational infrared spectroscopy analyses were performed using a Varian 600-IR Fourier-transform infrared (FTIR) spectrometer equipped with a Pike Technologies GladiATR accessory for attenuated total reflectance (ATR) measurements at a 45° angle, utilizing a zinc selenide crystal. The spectral range analyzed was from 400 to 4,000 cm⁻¹, with a resolution of 2 cm⁻¹ and 32 scans. For both FTIR readings and TG analyses, the samples were processed into a homogeneous form consisting of powder or fine grains. This approach ensured consistency in the analytical procedures.

3. Results and discussion

3.1. Basic characterization

The data presented in Table 7 reveals that the impregnation process was conducted with a sample moisture content of 11%, and the average final PCM content reached 7.11%. Initially, this impregnation content appeared to be lower than what might be deemed necessary to exert any significant influence on the resulting object's thermal properties. Additionally, a density of 0.72 (g/cm³) was observed, along with a 5.29% increase in weight on the pre-impregnated bamboo due to the application of PU resin.

Table 4. Summary of the average general characteristics of the samples, *Phyllostachys aurea*.

Average moisture content (%)		Medium weight (g)		Apparent basic density (g/cm ³)		Average mass increase after impregnation by PCM and application of PU resin	
Original	Post oven drying	Original	Post oven drying	Loss (%)	Original	PCM	Resina
29	11	137	125	8,76%	0,72	7,11%	5,29%

3.2. Hotbox essay

The results of the thermal tests are depicted in Fig. 8, 9, and 10, illustrating temperature profiles recorded by the thermocouples positioned within the setup, as detailed in Table 8. The samples underwent thermal testing encompassing both heating and cooling cycles (phases 1 and 2).

Table 8. Location and acronyms of the thermocouples used in the experiment.

Localização	Siglas
<i>External Air</i>	EA
<i>External Surface of sample</i>	ES
<i>Internal Surface of sample</i>	IS
<i>Internal Air</i>	IA

The results were presented individually for each sample (Fig. 8) and combined for better data comparison visualization (Fig. 9 and 10). The dashed and dotted lines represent the analysis 1 and the control samples (with PU resin and without PCM and raw bamboo culm respectively), while the solid lines represent the PCM-impregnated material (analysis 2) refere. As explained earlier, each color represents the average measurement of a pair of thermocouples positioned simultaneously in different regions.

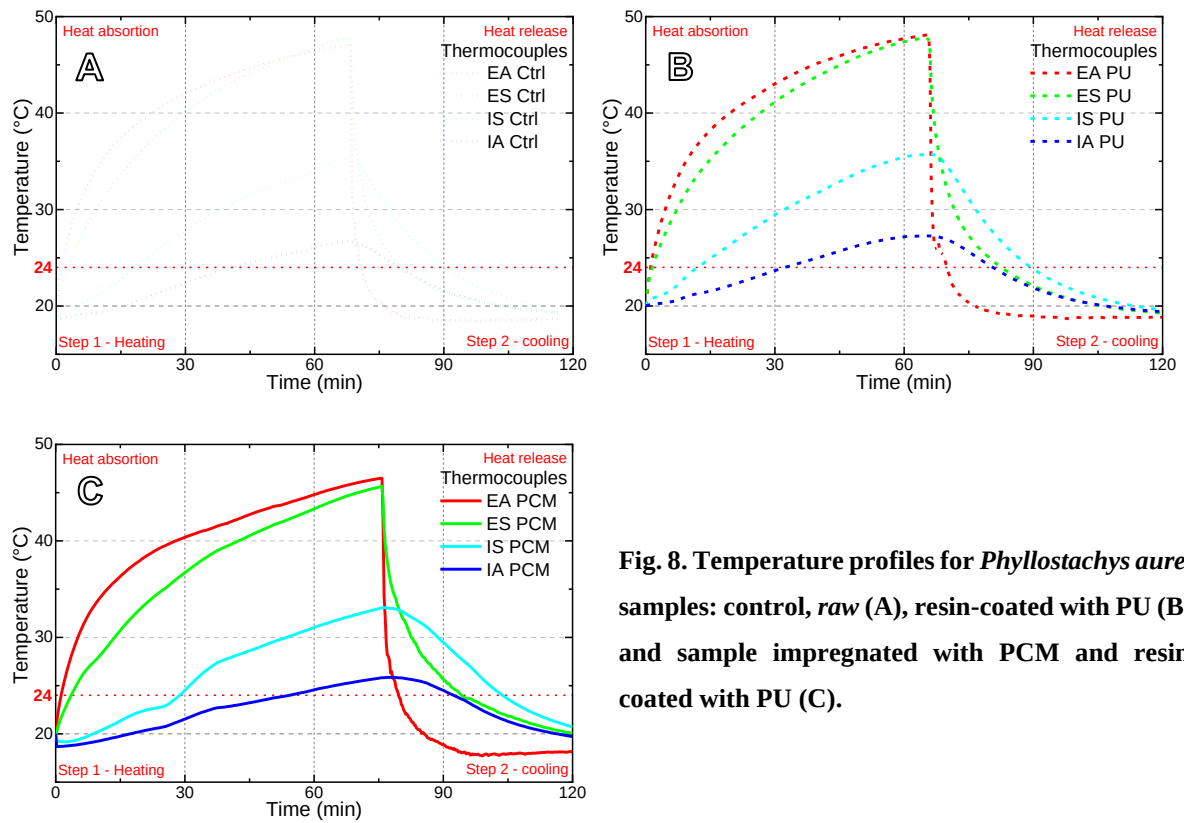


Fig. 8. Temperature profiles for *Phyllostachys aurea* samples: control, raw (A), resin-coated with PU (B), and sample impregnated with PCM and resin-coated with PU (C).

The results shown in Fig. 8 show that the temperature variation profile in all thermocouples of the control samples and those resin-coated with PU is quite similar (Fig. 8a and Fig. 8b). Similarly, in both samples, the temperatures of the external air and the external surface of the sample rise rapidly due to the heat emitted by the lamp. However, there is a significant delay in heating the sample's internal surface and even more so in the interior air of the passive chamber in the same samples. This delay is, however, much more pronounced when we look at the curve of the sample treated with PCM, highlighting that even the external surface of the PCM-treated sample experiences a slight delay in temperature increase.

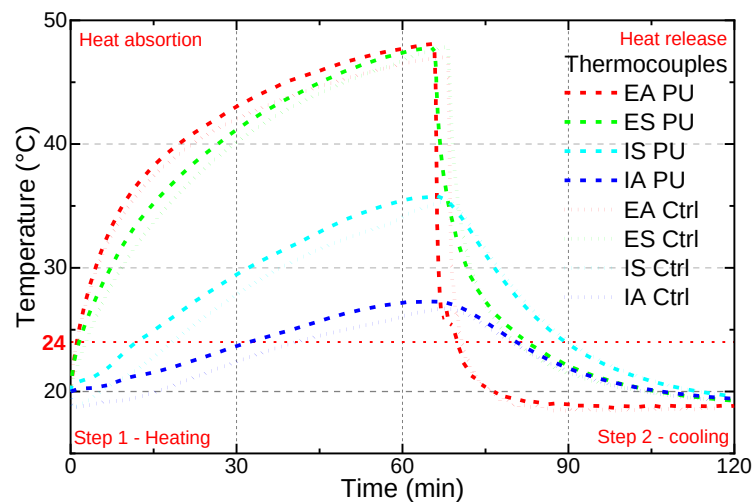


Fig. 9. Combined temperature profiles for sample raw (control), compared to resin-coated with PU sample.

Fig. 9 provides a clearer comparison between the samples, where it can be observed that the temperature of the resin-coated samples with PU was slightly higher in all thermocouples. This suggests a more rapid heat transfer with this treatment compared to the raw (control) samples. However, there is no visual evidence of a change in the temperature growth trend, as the curves exhibit a constant linear trend, with parallelism between the aforementioned treatments.

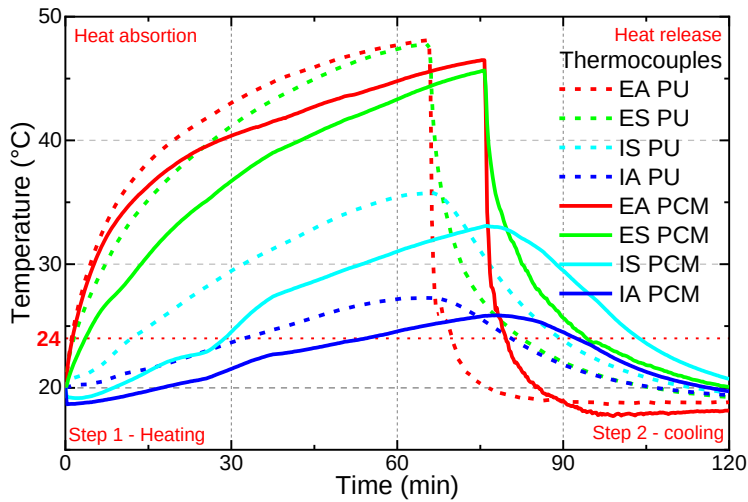


Fig. 10. Combined temperature profiles for sample resin-coated with PU, compared to sample impregnated with PCM and resin-coated with PU.

Fig. 10 compares the samples coated with PU resin to those impregnated with PCM. Notably, when the PCM-impregnated sample reaches approximately 24°C, the curve trends begin to shift. This shift coincides with the PCM undergoing a phase change, absorbing heat, and consequently delaying the temperature increase. For instance, while the bottom surface thermocouple (IS PU) of the resin-coated with PU sample takes approximately 15 minutes to reach 25°C, the PCM-impregnated sample (IS PCM) requires approximately 30 minutes, indicating a 50% longer time to reach the same temperature. This result demonstrates the efficacy of PCM-impregnated *Phyllostachys aurea* bamboo culms for thermal energy storage.

3.3. Visual analysis

Under 10x magnification, as depicted in Fig. 11a and 11b, it is possible to discern and delineate the anatomical structures that make up bamboo, along with the high content of voids at various scales. Notably, larger voids are observable within the sap-conducting vessels within the parenchyma, a structure primarily constituted of lignin that forms the cellular framework. In Fig. 11a, these voids are impregnated with solid-state PCM, imparting a waxy appearance, a phenomenon absent in Fig. 11b, where the raw bamboo stalk remains in its natural state, rendering the sap-conducting vessels as distinct dark polygonal shapes. Fig. 11c,

11d and 11e with a 125x magnification, it is possible to observe more detailed view, including the bundle of sap-conducting vessels with more pronounced voids, as well as intercellular and intracellular spaces of the raw bamboo culm.

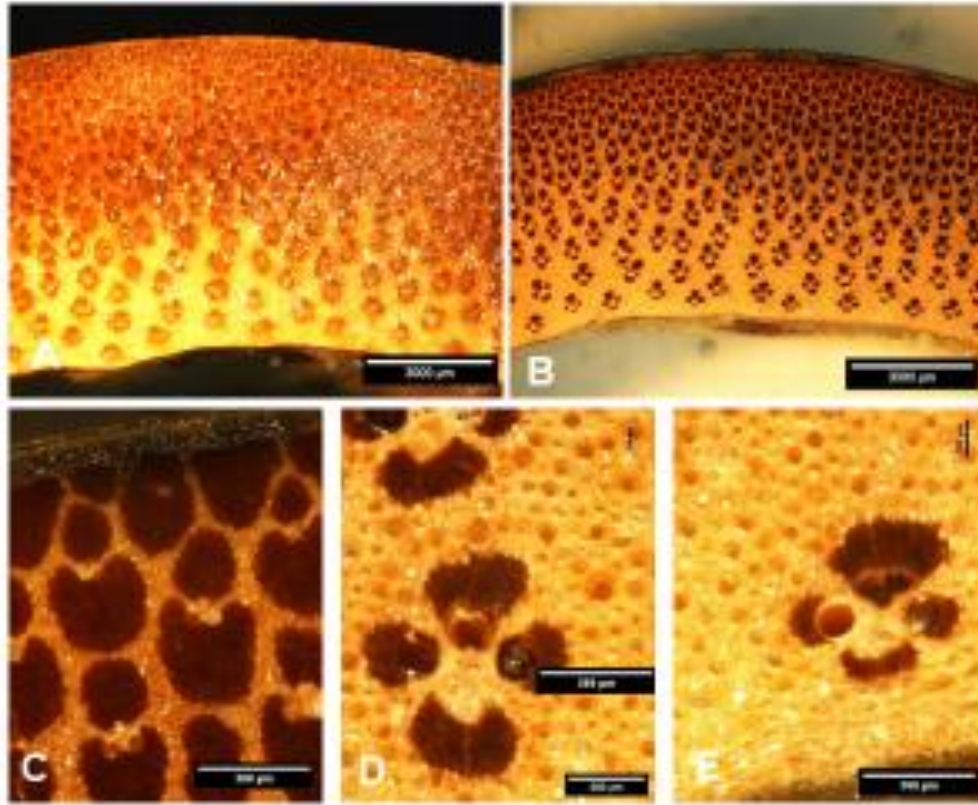


Fig. 11. Images obtained by optical microscopy (at 10x magnification) of the internodal cross-sections of *Phyllostachys aurea* bamboo culm with PCM impregnation (A) and without impregnation (B), and an images at 125x magnification of the same transversal cut of de outer (C), mid (D) and the inner part (E) of the culm wall.

Fig. 12 presents a sequence of timed images, captured at 20-second intervals (Fig. 12a, b, c, and d), on a macroscopic scale. These images document the melting and subsequent release of PCM impregnated within bamboo when subjected to temperatures exceeding 24°C, its melting point. It is important to note that this leakage is exclusively observable in the cross-sectional cut section of bamboo, emphasizing the potential loss in the absence of PU resin sealing in this

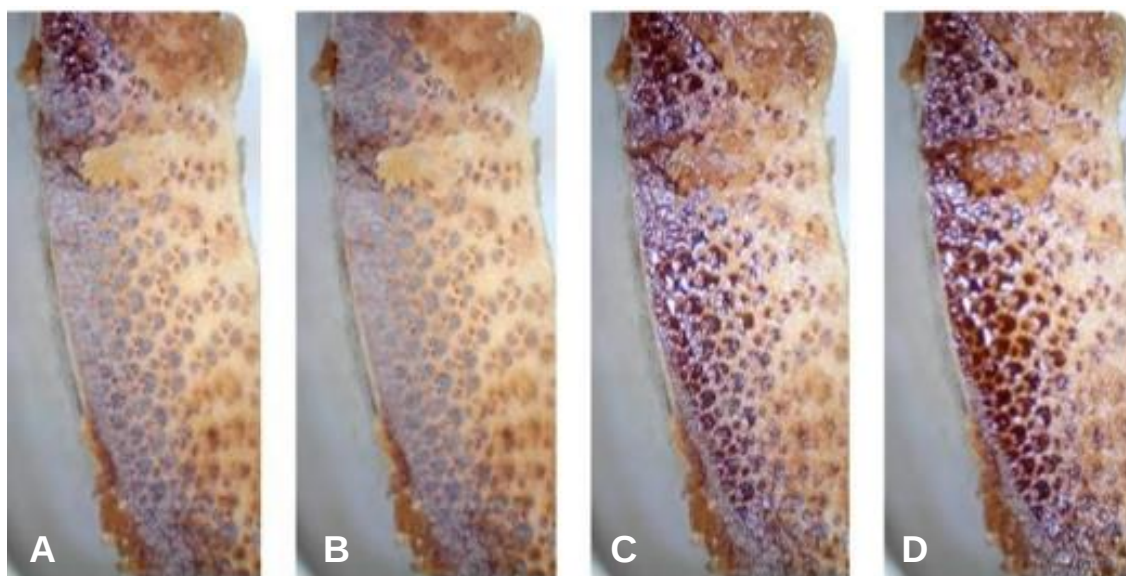


Fig. 12. Successive images on a macroscopic scale extracted from the melting process of PCM24 impregnated in *Phyllostachys aurea* bamboo culms, taken every 20 seconds from the 20s (A), 40s (B), 60s (C), to 80s (D).

Fig. 13 offers a series of sequential images (Fig. 13a, b, c, d, and e) on a macroscopic scale, also captured in a time-lapse format, showcasing the process of impregnation with an aqueous-based dye within a cross-section of bamboo that had been previously oven-dried without vacuum application. These images illustrate the rapid absorption of the liquid by the porous bamboo structure.

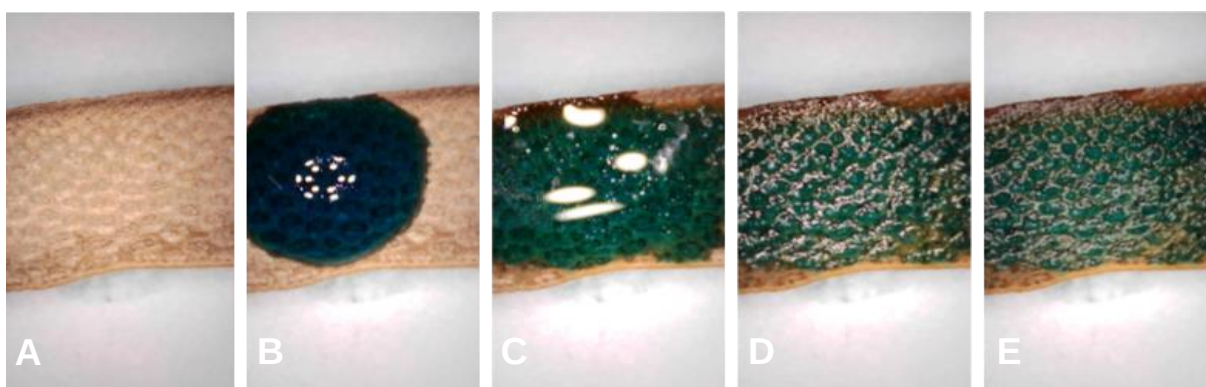


Fig. 13. Successive images on a macroscopic scale of the bamboo *Phyllostachys aurea* dye impregnation process, chronologically taken every 20 seconds from 0s (A), the 20s (B), 40s (C), 60s (D) to 80s (E).

3.4. Chemical characterization

Fig. 14 presents the thermogravimetry (TG) and derivative thermogravimetry (DTG) curves, offering insights into the chemical composition of the samples. Generally, the initial mass loss, observed up to 100°C, arises from the release of free water within the

material during the early moments (Guimarães 2023; Guimarães et al. 2023) Further mass loss events are discernible in these curves, including: Inthe natural bamboo sample, aninitial peak is noticeable, occurring roughly between 250 and 320°C, corresponding to the degradation of hemicellulose (typically between 150 and 350°C (Kim et al. 2006). Subsequently, a sharp peak centered at 348°C corresponds to the degradation of cellulose. Finally, a lower-intensity peak, slightly above 400°C, likely corresponds to the degradation of lignin, typically occurring within the range of 250 to 600°C, all constituents found in substantial proportions in the vegetative tissues of the examined bamboo species. Inthe PCM-treated sample curve, a peak emerges shortly after 200°C, distinguishing it from samples treated without PCM. This disparity results from the degradation of PCM, an organic ester, begins at relatively low temperatures (Poletto et al. 2014) with a center around 234°C. These samples also exhibit corresponding peaks akin to those observed in natural samples of these plant tissues. Regarding the sample treated only with PU resin, it's essential to consider that, according to literature sources (Azevedo et al. 2009; Müller et al. 2020), polyurethane undergoes mass loss in two decomposition stages. The first stage starts at 240°C and ends at 350°C, related to the rupture of urethane bonds. The second stage starts at 500°C, pertains to the decomposition of ester bonds within the polyol. These peaks are discernible despite potential overlap with hemicellulose degradation occurring at similar temperatures. These results confirm the presence of PCM in the samples and underscore the efficacy of the proposed method for PCM incorporationinto bamboo culms.

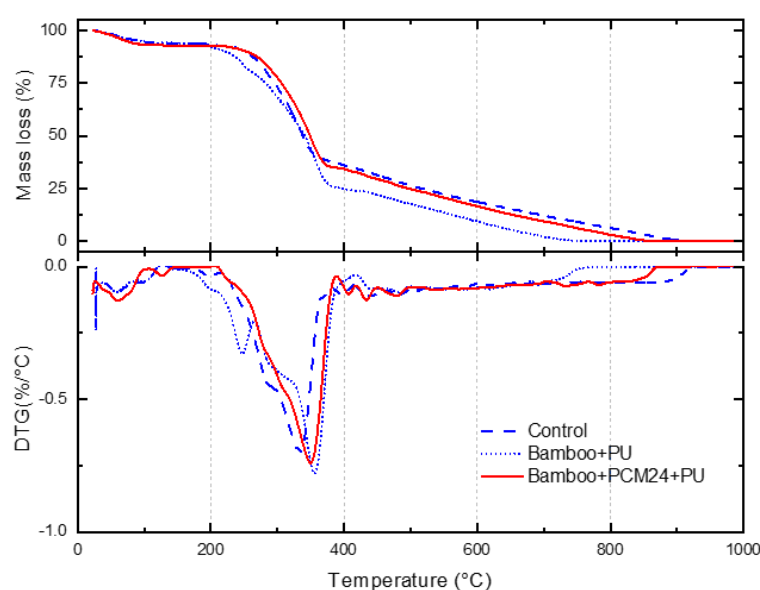


Fig. 14. Thermogravimetric analysis curves: TG and DTG of raw culm of *Phyllostachys aurea*, treated with PU and PCM.

Fourier Transform Infrared Spectroscopy (FTIR) is employed for identifying functional groups, primarily in fibers (Rodrigues and Galzerani, 2012), and chemical bonds in materials. The result is obtained from the absorption of radiation at various wavelengths in scans ranging from 4000 to 500 cm^{-1} (Fredericci et al. 2016), as observed in the results shown in Figure 15. The active peaks obtained in all bamboo samples exhibit a remarkable degree of similarity, suggesting minor variations in intensity. Existing literature suggests that for each absorbance band, there are peaks associated with characteristic chemical functional groups in specific materials, including lignocellulosic substances (Sánchez et al. 2017).

The primary chemical elements within bamboo encompass lignin, cellulose, hemicellulose, starch, silica, and pectin. According to (Liu and Fei, 2013) the bands between 1600 and 1450 cm^{-1} correspond to the characteristic region of lignin, hemicellulose, cellulose, and pectin, with peaks between 1558 and 1508 cm^{-1} indicating the presence of lignin, as well as peaks between 3338 and 1234 cm^{-1} . Around 3000 cm^{-1} , low-intensity peaks are observed in sample treated with PCM, related to the stretching of $=\text{C}-\text{H}$ bonds in alkenes. These bonds exist in the polymers due to the butadiene monomer (Guimarães et al. 2023) Two peaks can be observed at 2919 and 2850 cm^{-1} , related to the stretching of $\text{C}-\text{H}$ bonds in alkanes. These bonds are, present in bamboo fiber components (cellulose, hemicellulose, and lignin) and soluble extractives, as well as in the polyurethane resin (PU) polymer structure (sample A), resulting in an increase in the intensity of these peaks in treated samples. A peak is also observed at 1735 cm^{-1} , ascribed to the stretching of $\text{C}=\text{O}$ bonds. This peak is attributed to the acetyl ester and uronic acid groups in hemicelluloses or the ester linkage of ferulic and p-coumaric acid groups in lignin and/or hemicellulose (Ferreira et al. 2017). An increase in the intensity of these peaks is observed in sample without PCM, probably due to the $\text{C}=\text{O}$ bonds of polymer carboxylic groups. However, in sample containing PCM, these peaks tend to decrease in intensity and shift slightly, possibly due to interactions between the PCM and $\text{C}=\text{O}$ groups present in bamboo components (Guimarães et al. 2023). In the region between 1300 and 1000 cm^{-1} , some peaks related to the stretching of $\text{C}-\text{O}$ bonds can be observed, characteristic of alcohol, carboxylic acids, ester functional groups, or ethers present in bamboo fiber components or PU polymer. In the range between 1220 and 1133 cm^{-1} , there was a decrease in peak intensity in sample containing PCM, presumably related to interactions between PCM and bamboo or polyurethane components.

The 900 and 896 cm^{-1} peaks can be attributed to β -glycosidic linkages between xylulose units in hemicellulose. The bands between 1458 and 1373 cm^{-1} may be indicative of typical cellulose absorption. The 1630 and 1639 cm^{-1} peaks are attributed to stretching vibration of vibrations, signifying the presence of starch and H_2O , respectively (Pedrangelo 2020). According to (Liew et al. 2015), the band from 3200 to 3500 cm^{-1} (3338 cm^{-1}) usually indicates an increase in hydroxyl groups, and the 2921 cm^{-1} peak indicates polysaccharide CH. The 561 cm^{-1} peak indicates the presence of CBr. The 1735 cm^{-1} peak indicates the C=O bond. These findings collectively provide valuable insights into the chemical composition and structural attributes of the investigated bamboo samples.

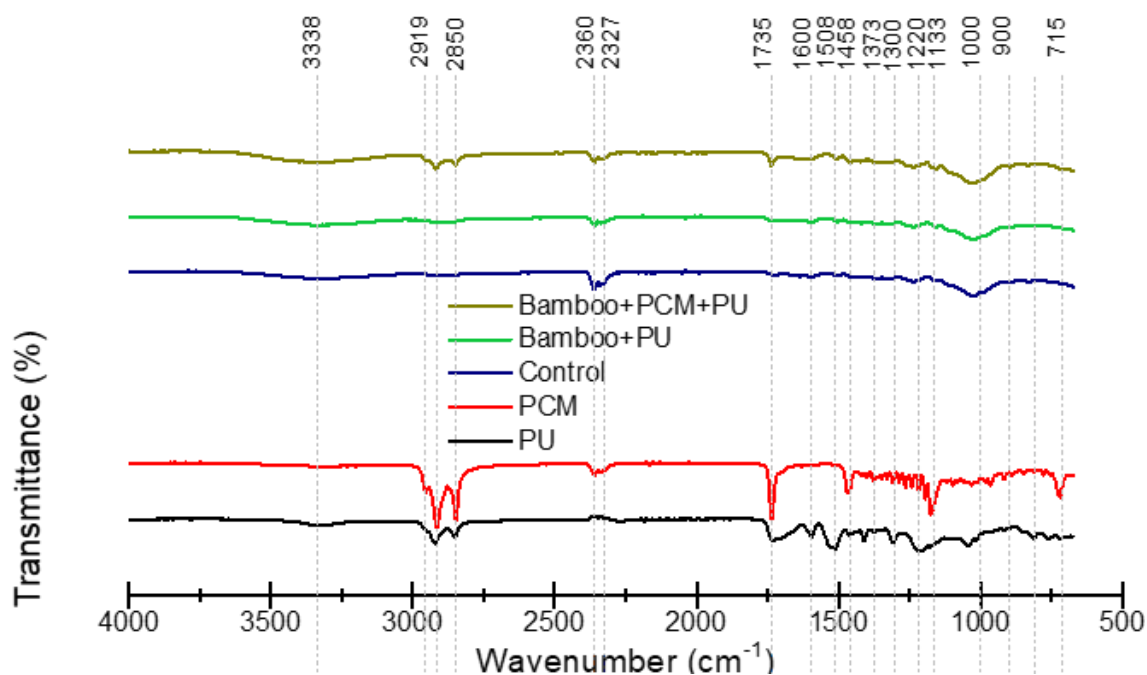


Fig. 15. FTIR spectroscopy of raw culm of *Phyllostachys aurea*, treated with PU and PCM, and samples with raw PCM and PU.

Conclusions and recommendations

This study presents a straightforward process for utilizing *Phyllostachys aurea* bamboo culms as a supportive matrix for phase change materials (PCMs). These bamboo culms are impregnated using negative pressure while still in their natural cylindrical shape and later resized for practical use, and sealed with polyurethane resin to create a thermally efficient composite material. Thermal analysis demonstrated the material's ability to anchor temperature around the specific PCM melting point (24°C), highlighting its functionality. Moreover, FTIR, TG, and DTG analyses reveal that no significant chemical reactions

occur during the impregnation process, which is beneficial for its application in phase change thermal energy storage applications. This process ensures the PCM efficiently penetrates the porous structure of the bamboo culms. As a result, the developed composite material holds promise as a versatile bamboo-based composite material that combines multiple functions and has the potential for development in energy-saving applications related to building thermal conditioning. It is expected to enhance the energy efficiency of buildings and other related purposes. The results of this work also demonstrate that it is advisable to conduct a more in-depth analysis of the possibilities of impregnating bamboo culms with PCM. Several species with specific characteristics may likely have more interesting capabilities for this application, as well as other impregnation methodologies and thermal analysis techniques that can be evaluated for process improvement.

Acknowledgment

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Conflict of Interest

It is hereby confirmed that the manuscript has been read and approved by all the named authors, and there is no conflict of interest. All regulations of our institution, including intellectual property rights, have been followed, and there are no impediments to publication.

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ARTICLE 2

Highlights

A comparative study of four different species bamboo culms as a carrier for thermal energy storage through phase change material impregnation

Fabício Rezende Fontenelle

- *Dendrocalamus giganteus* species with larger dimensions in terms of wall thickness, distance between nodes, and culm diameter and length, along with lower density, exhibited greater efficiency for the desired purposes demonstrating a significant temperature anchoring compared to the other species.
- *Dendrocalamus giganteus* species had a higher PCM impregnation content in a larger volume of material, making it, at first, the best-qualified species among those studied.
- The relationship between the prior density of bamboo culms and their impregnation capacity was confirmed in this experimental campaign.
- The methodology for the impregnation was also improved by an immersion process in an environment subjected to negative pressure through vacuum pumping, resulting in a higher PCM content in the samples.
- Chemical and ultrastructural visual characterizations conducted confirmed PCM impregnation as well as the virtually inert chemical behavior of PCM within the bamboo composition.

A comparative study of four different species bamboo culms as a carrier for thermal energy storage through phase change material impregnation

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ABSTRACT

In a quest for sustainability, where the construction industry performs a significant role in environmental impacts, materials research plays a relevant path seeking the environmental efficiency of buildings through the use of materials from renewable sources, such as bamboo. In climates characterized by high-temperature variations, the incidence of solar radiation and the absorption of heat by building enclosures becomes crucial therefore materials that have advantageous thermal properties contribute to improve environmental comfort by reducing the use of high-consumption active cooling systems. This investigation seeks to unite the naturally porous lignocellulosic biomass of bamboo, with its advantageous properties, both in the carbon fixation from the atmosphere and for its physical-mechanical resistance, with the use of phase change material (PCM) and its thermal properties. In order to evaluate the best features, we used culms of four different species: *Bambusa tuldoidea*, *Dendrocalamus giganteus*, *Guadua augustifolia* and *Phyllostachys aurea* as a reservoir for PCM to give the resulting object the characteristics of thermal efficiency due to the high thermal storage capacity carried out by the PCM whose effective potential has been explored. Thermal variation tests showed that the impregnated bamboo samples effectively reduce temperature fluctuations by tending to anchor it to the PCM's specific change-of-phase temperature. Three different types of bamboo samples were comparatively analyzed: raw culms, culms sealed with polyurethane resin (PU), and impregnated with PCM also sealed with PU. The production proceedings sought economy and minimal processing to facilitate its reproducibility. In terms of anatomical structure, the pores within bamboo culms provided enough space to store the PCM and obtain a high heat storage capacity. The tightness against PCM leakage in its liquid state, provided by the PU seal, ensured that there would be no subsequent loss due to flow. This study demonstrated that PCM-impregnated bamboo culms are promising for building temperature regulation applications and that the variation present in the anatomical morphology and physical characteristics of each species influences the quality of the results obtained.

1. Introduction

Bamboo is a sustainable natural resource that holds great potential for significantly reducing the environmental impact of the construction industry. This versatile plant appears to be custom-made for use in building structures. The availability, ease of distribution, rapid maturation for harvesting, and favorable physical and mechanical properties of this material makes it an ideal choice for construction applications. It can serve as a sustainable alternative to materials derived from non-renewable resources or native forests that are exploited without proper management and conservation Palani, Goutham, Ayyappadasan and Praveena (2020). Alternatively, cutting-edge research into improving materials' thermal capacity and efficiency has been successfully exploring the potential of Phase Change Materials (PCMs). These materials have the capacity to store latent energy during their phase transformation (Liquid-Solid or Solid-Liquid), and when incorporated into a building, they can effectively stabilize temperature fluctuations, thereby decreasing the necessity for artificial climate adjustments in response to natural climate variations Zhang, Feng, Shi, Wang, Jin, Tian, Li, Wang, Zhao and Yan (2021). In these materials when a phase change occurs due to a temperature

change that prevents the PCM from remaining in its previous state, there is a reorganization of intermolecular chemical bonds. This modification requires energy movement in both endothermic and exothermic directions, depending on the direction of the transition Sharma, Tyagi, Chen and Buddhi (2009). In practice, phase change materials, at their melting or evaporation points, solidification or condensation, continue to largely absorb/release heat without altering their temperature for a certain period, resulting in a latent energy accumulation during this state transition, as illustrated in Figure 1 with a central "plateau."

According to Cabeza, Castell, Barreneche, de Gracia and Fernández (2011), the main advantage of latent heat storage is the high storage density within small temperature ranges, making it suitable for both heating and cooling of buildings. It can be incorporated either as a passive system or in active climate control systems. Various research efforts have sought to identify structures that could serve as receptacles for PCMs to contain these substances in their various physical states, which are essential for their thermal efficiency.

Several chemical substances have been employed as PCMs, with the most common ones being organic, including primarily paraffins and fatty acids. There are also inorganic substances like metals and hydrated salts and a mixture of organic and inorganic substances in various forms, commonly

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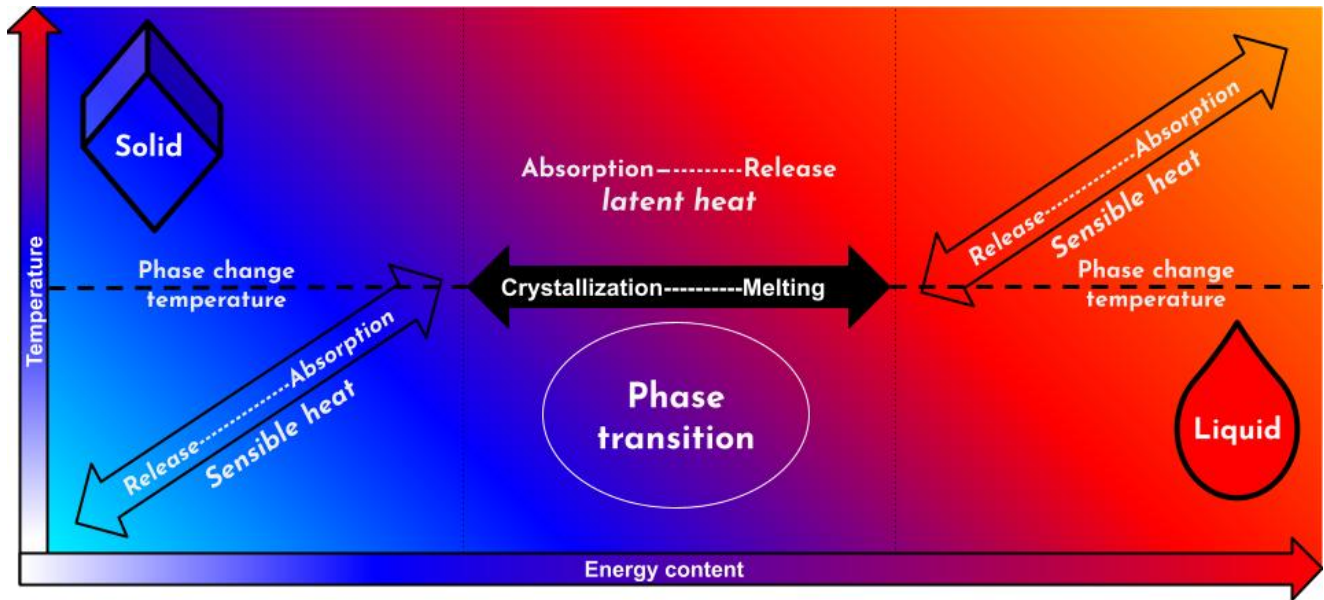


Figure 1: Energy content x temperature - the behavior of PCMs.

known as eutectic PCM Váz Sá, Almeida, Sousa and Delgado (2014).

Among the various materials used for PCM containment, porous materials have demonstrated interesting capabilities in this sense Huang, Chen, Li, Atinafu, Gao, Dong and Wang (2019). Examples include lightweight aggregates, recycled inerts, porous fibers, textile systems, etc Kuhn, Guimarães, Fontenelle, Ferreira and Corrêa (2023).

This current research aims to combine the existing capacities and properties of lignocellulosic materials, such as bamboo, which is naturally porous, with the thermal efficiency induced by the possible impregnation of PCM into the voids of its anatomical structure.

Most of the four bamboo species studied in this paper (i.e., *Bambusa tuldoidea*, *Dendrocalamus giganteus*, *Guadua augustifolia* and *Phyllostachys aurea*) are abundantly found in Brazilian territory and are often used for rustic and artisanal purposes in traditional communities. Rios and Farias (2021); Vasata, Santos, Santos, Cadorin, Portes, Dalcanal, Novak and Ostapiv (2021). Nevertheless, its industrial use or processing for commercially advantageous situations remains incipient. This research seeks to explore another potential benefit that leverages the best characteristics of these materials in conjunction with PCM Fontenelle and Ferreira (2024); Fontenelle, Ferreira, Guimarães and Kuhn (2023). A bio-based organic PCM with a phase change temperature of approximately 24 °C was selected for this work. Therefore, the primary objective is to evaluate the influence of the species culm anatomical differences as a reservoir for PCM within its natural porosity. The resulting object should retain the qualities of bamboo while acquiring the inherent thermal capacity of the PCM in sufficient quantities for its functionality.

2. Materials and methods

Four species of bamboo culms have been used and are listed below:

- ***Bambusa tuldoidea* (B):** commonly known as *Taquara* in Brazil. It was harvested at coordinates UTM Zone 23k: latitude: 7623 342.24 mS and longitude: 537 003.83 mE. It is an abundant clumping exotic species in the Brazilian territory, especially in the Southeast region, widely used for demarcating rural plots and for making baskets and temporary building enclosures but with limited commercial exploitation in Brazil (fig. 2a).
- ***Dendrocalamus giganteus* (D):** commonly known as *Bambu gigante*. Harvested at coordinates UTM Zone 23k: latitude: 7622 850.81mS and longitude: 545 461.37 mE. Abundant clumping exotic species in the Southeast region of Brazil, used in civil construction and for producing slats for laminates, with large dimensions (fig. 2b).
- ***Guadua augustifolia* (G):** commonly known as *Guadua*. Harvested at coordinates UTM Zone 23k: latitude: 7586 013.88mS and longitude: 664 305.36 mE. An abundant invasive species in the Andean countries, extensively used in its native regions for furniture manufacturing and construction but relatively under-explored commercially in Brazil, possessing excellent physical-mechanical resistance and high durability compared to other species (fig. 2c).
- ***Phyllostachys aurea* (P):** commonly known as *Canadá Índia* in Brazil. It was obtained at coordinates UTM Zone 23k: latitude: 7623 194.48 mS and longitude: 545 573.09mE. This species is an abundant, spreading



Figure 2: Clumps of the four bamboo species: *Bambusa tuldoidea* (a), *Dendrocalamus giganteus* (b), *Guadua augustifolia* (c) and *Phyllostachys aurea* (d). Commercial CrodaTherm 24 PCM (e). Pieces of bamboo culms used in this research: *B. tuldoidea*, *D. giganteus*, *G. augustifolia*, *P. aurea* respectively from left to right (f), and (g) resin used for sealing, PU Vegetal – type "V" commercial.

exotic species in the Brazilian territory and it is widely used in other parts of the world but also underexplored in Brazil. It possesses high physical-mechanical resistance and durability compared to other similar materials Sánchez Vivas, Mullins, Cunningham and Mihelcic (2019) (fig. 2d).

In Figure 2, we can observe the clump from which each species was extracted (a, b, c and d) and the sections of stalks that were already selected, cured and dried for impregnation (f).

The phase change material (PCM) used was CrodaTherm 24 (fig. 2e), a product with a chemical composition in trade secret and with a melting temperature of approximately 24°C and a solidification temperature of approximately 21°C. It was obtained through a donation from Croda International Plc Crodatatherm (2020). This PCM has a specific temperature range for phase change that is very close to the ideal thermal comfort temperature for use in buildings The physical properties of this PCM are found in Table 1.

Additionally, a PU Vegetal – Type "V" sealing resin (fig. 2g) was used, which is a two-component polyurethane waterproofing agent of vegetable origin (derived from castor oil - *Ricinus Communis*), with an amber color Sinergia

(2020). This resin has application and performance characteristics suitable for the sealing, durability, and waterproofing requirements of the research. Its natural origin from a renewable plant resource adds to its appeal.

The research methodology essentially involved the following processes: collection and preparation of samples for analysis, essential physical and morphological characterization of the collected bamboo, thermal analysis to confirm the effect of impregnated PCM, macroscopic and microscopic visual examination of the samples, as well as chemical characterization.

2.1. Cutting and Preparation of Stalks and production of essay specimens

Three distinct treatments were considered to the four species: raw bamboo culm (reference group, without any treatment, referred to as "Control"), bamboo culm sealed with PU (referred to as "PU"), and bamboo culm impregnated with PCM and subsequently sealed with PU (referred to as "PCM"), as summarized in Table 2. These treatments were selected to investigate not only the influence of PCM but also any potential effects, particularly concerning thermal behavior, associated with the application of applying the PU resin.

Table 1

Physical properties of CrodaTherm 24 Guimarães (2023); Guimarães, Gomes, Oliveira de Araújo, Tadeu Lopes, da Gloria, Toledo Filho, Koenders, Caggiano, Mankel, Nazari Sam, Mendes de Andrade and Ferreira (2023).

Property	Typical Value	Unit
Thermal properties by Differential Scanning Calorimetry (DSC)		
Peak melting temperature	24	°C
Latent heat (melting)	184	kJ/kg
Peak crystallisation temperature	22	°C
Latent heat (crystallisation)	−182	kJ/kg
Thermal properties by three-layer calorimetry (3LC)		
Peak melting temperature	23	°C
Total heat capacity (melting)	207	kJ/kg
Peak crystallisation temperature	23	°C
Total heat capacity (crystallisation)	213	kJ/kg
Other properties		
Bio-based content	100	%
Density at 20 °C (solid)	906	kg/m ³
Density at 40 °C (liquid)	843	kg/m ³
Flash point	226	°C
Specific heat capacity (solid)	3.7	kJ/kg °C
Specific heat capacity (liquid)	2.2	kJ/kg °C
Volume expansion 20–40 °C	7.5	%
Thermal conductivity (solid)	0.22	W/m °C
Thermal conductivity (liquid)	0.16	W/m °C
Thermal cycles without change in properties	10,000	cicles

Table 2

Treatment and denomination of samples used in the thermal test (Hotbox).

4 Bamboo species	3 Treatments	Objective	Denomination
<i>Bambusa tuldoidea</i>	Raw bamboo culm - without treatment	control	Ctrl
<i>Dendrocalamus giganteus</i>	Bamboo culm sealed with PU	analysis 1	PU
<i>Guadua augustifolia</i>	Bamboo culm impregnated with PCM and sealed with PU	analysis 2	PCM
<i>Phyllostachys aurea</i>			

From the bamboo samples collected, those with the most appropriate suitable dimensions for the research objectives were selected. The sections chosen were extracted from the middle third of the bamboo stalk, with both the basal third and the upper third being excluded from consideration and then discarded. All procedures were carried out in accordance with the Brazilian bamboo standard NBR 16828-2 ABNT (2020). The selection criteria were primarily based on factors such as the relationship between diameter, node spacing, and wall thickness. It is worth noting that the central portion of the bamboo culm is the most resistant to stress Hidalgo-Lopez (2003). Additionally, this central region boasts a more uniform morphology characterized by regular node spacing and a cylindrical cross-section.

The collected bamboo stalks were subjected to a two-week period of natural drying or curing, with controlled mass variations, ensuring that they were protected from exposure to adverse weather conditions. Following this, they were longitudinally cut to the appropriate dimension of 250mm (figure 3a), enabling them to fit comfortably into the thermal test chamber for the hotbox essay and underwent cross-sectioning to create curved strips (Fig 3 a, b and c).

The procedure followed a similar approach to the one employed in the production of slats (as illustrated in Figure 3d). To fulfill the Hotbox testing criteria, we aimed for minimal gap tightness to prevent excessive air flow. This involved the removal of septa or nodes found in the stalks, using tools like chisels and mallets. Additionally, each test specimen was appropriately labeled for identification purposes. It's worth noting that each bamboo species possesses unique dimensions and characteristics based on their natural morphology. Consequently, we had to adapt both the procedure and the final slat shape of the samples to conform to these aspects and achieve the required overall width of 175mm, as depicted in table 3.

These prepared specimens were then placed in an oven for induced drying (fig. 3e), following established procedures documented in literature Forest Products Laboratory (2010); Moreschi (2005); Moura, Dalla and Vieira (2018)..

For PCM impregnation as the samples already had their final form for use in the thermal box test the test specimens were placed in plastic containers and immersed in PCM in liquid state (fig. 3g and h). Subsequently, these containers

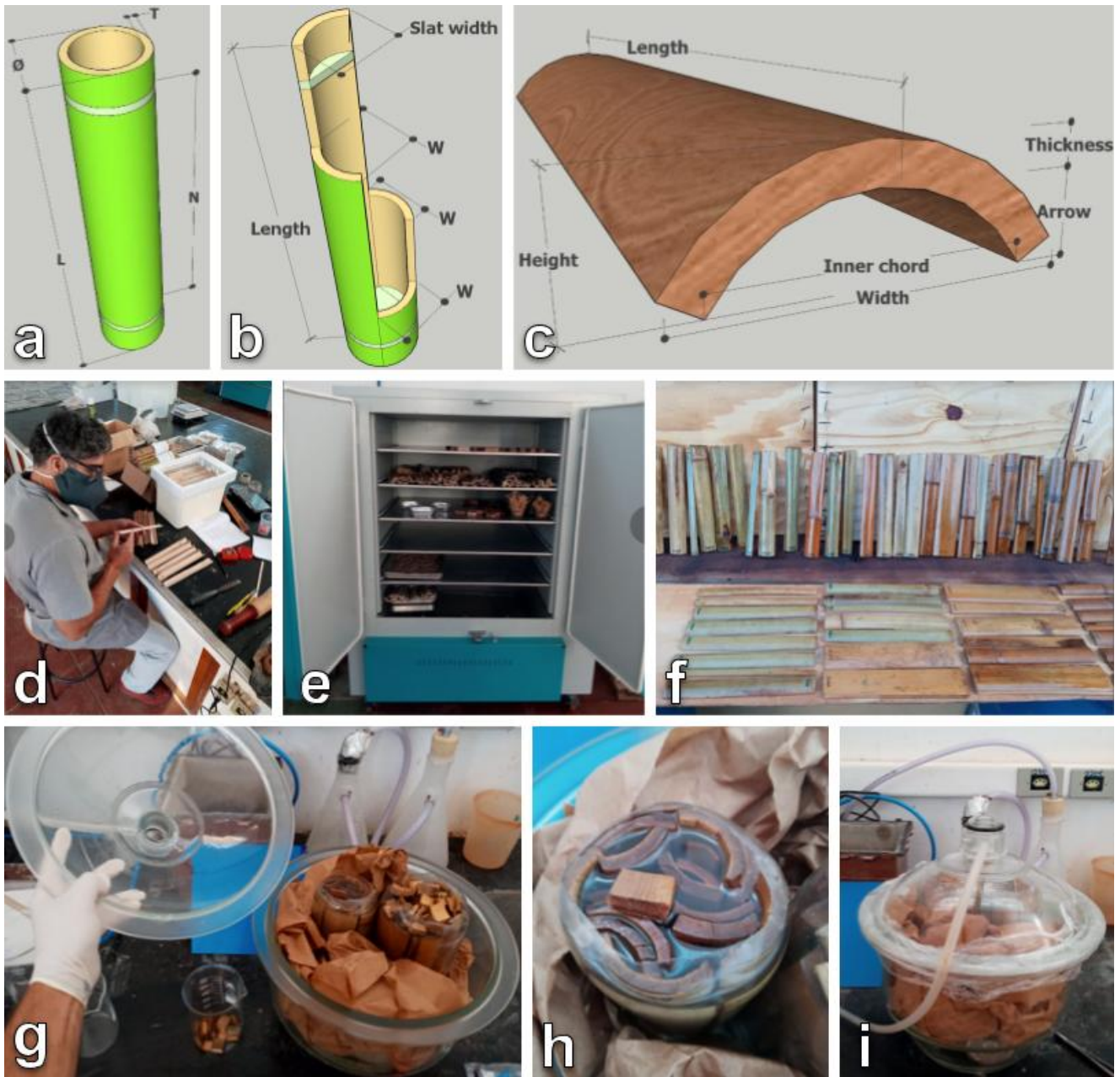


Figure 3: The original shape of the sample from the impregnation process is depicted in (a), and (b) illustrates the schematic of the longitudinal cut of the stalks followed by the expected final slat shape of the slat (c). It's also possible to observe the manufacturing process of the test specimens (d), the drying process (e), sample conditioning for impregnation (g), immersion of test specimens in PCM (h), and vacuum treatment (i), in addition to the organization and procedure for applying PU resin by spray (f).

were placed in a laboratory desiccator connected to a vacuum pump (fig. 3i), which had previously been intercepted by a Kitasato setup to prevent contamination of the pump by liquid PCM. It's worth noting that due to the ambient temperature being above 24°C, there was no need to heat the PCM.

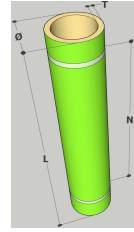
The negative pressure pumping was carried out until confirming the vacuum in the desiccator, as indicated by the pressure shown on the pump's manometer. In this vacuum condition, it is possible to observe the appearance of bubbles

on the cross-sectional surfaces of the bamboo culm samples, which represent the release of air from the porosity within the object's anatomy. This process was repeated until the appearance of bubbles ceased, which occurred after approximately 24 hours. After completing the impregnation, the samples were drained, and excess PCM was removed using absorbent paper towels. Subsequently, they were stored in a refrigerated environment (at approximately -6°C) to prevent PCM loss due to leakage resulting from its liquefaction.

Table 3

Morphological characteristics of the original samples.

Species	Culms Average general dimensions (mm)			Average characteristics of the nodes	
	Diameter Ø	Length L	Wall thickness T	Amount N	Average distance (mm) N
<i>Bambusa tuldoidea</i>	040	250	05	0	400
<i>Dendrocalamus giganteus</i>	140	250	08	0	450
<i>Guadua augustifolia</i>	060	250	06	1	300
<i>Phyllostachys aurea</i>	040	250	05	1	190



The sealing process was accomplished by mixing the PU resin components, but with a solvent dilution to enable the use of a compressed air spray gun. There was also a need to carry out the process quickly due to the rapid drying of the PU resin. The test specimens were placed on a suitable support for easier application (fig.3f). As the ambient temperature was below 24°C on the day of the procedure, it was possible to carry it out in an open space.

2.2. Basic characterization

In order to establish correlations between observed phenomena and the unique properties of each material, various general aspects were assessed throughout the process, including morphological and anatomical characteristics, as shown in Table 3.

Moisture content measurements were conducted using the electronic sensor Stanley model STH77030X. The samples were weighed after undergoing natural air drying to reach hygroscopic equilibrium Forest Products Laboratory (2010); Moura et al. (2018); Zen, Monteiro, Schaeffer, Kaminski and Klitzke (2019), and the determination of apparent density was the ratio between the dry mass (weighed using a precision scale following oven drying) and the water-saturated volume (determined using the displaced liquid method based on Archimedes' principle), while considering the irregular shape of the samples Forest Products Laboratory (2010); Moreschi (2005). The mass measurements were also taken before and after impregnation with PCM and subsequent application of the PU sealing resin, thus enabling the determination of the content of these substances in the final sample.

2.3. Hotbox essay

For the thermal tests, a laboratory-developed thermal box setup was utilized due to the absence of equipment capable of directly measuring the thermal behavior of the samples. This setup was modeled after an instrument designed for measuring thermal insulation capacity, commonly referred to as a "hotbox" Eugênio (2016);Terra (2018). It involved the use of two 8-liter thermal insulation boxes made of polystyrene (EPS) with an approximately 20 mm thickness. These boxes were stacked with an EPS support, which introduced a septum between them, serving as the placement area for the samples to be evaluated, effectively acting as a

diaphragm. The objective of the test was to assess the attenuation of thermal load between the two thermally isolated environments with initially equal temperatures Fontenelle and Ferreira (2024).

One of the boxes was equipped with a heat-emitting element, in this case, an incandescent bulb (glass bulb with a Tungsten filament and E27 non-ferrous socket, with a power of 15 W and a voltage of 127V), referred to as the "active chamber." The other box, termed the "passive chamber," received the heat variation from the active chamber, which was "filtered" or attenuated by the samples, creating a barrier or obstacle between the two environments, as outlined in the scheme presented in Table 4.

To ensure accurate temperature measurements, eight type K thermocouples were employed in a data collection system with temperature measurement and recording capabilities, boasting an accuracy of four decimal places in °C. Temperature readings were periodically recorded at predefined time intervals using software provided by the manufacturer of the commercial equipment, the Pico Technology USB TC-08 thermocouple data logger with PicoLog data logging software.

To enhance the setup's reliability, a layer of commercial aluminized foil was applied to the surface of the active chamber's box as a coating (Fig. 4a). This prevents overheating caused by the light bulb from damaging the EPS box wall. Additionally, within the sample placement area, an EPS-made barrier was embedded to securely hold the test specimens and prevent any gaps that might allow air passage between the chambers. Given that the samples were irregular materials without precise packaging (fig. 4c), ensuring a snug fit was crucial to eliminate gaps or openings. An outer layer of insulation was also added to the setup using 12 cm thick EPS plates forming a chamber around the experiment (Fig. 4b).

To conduct the experiment, it was important to note that the PCM used had a melting temperature of approximately 24°C, and the heat storage process and the phenomenon under investigation occurred within this temperature range. Consequently, the experiment was planned to allow the temperature to traverse this range with a substantial safety margin both above and below this value. This was necessary to observe the phenomenon in both its heating and cooling phases. The experimental procedure commenced with the organization of the thermometers and parameters in the

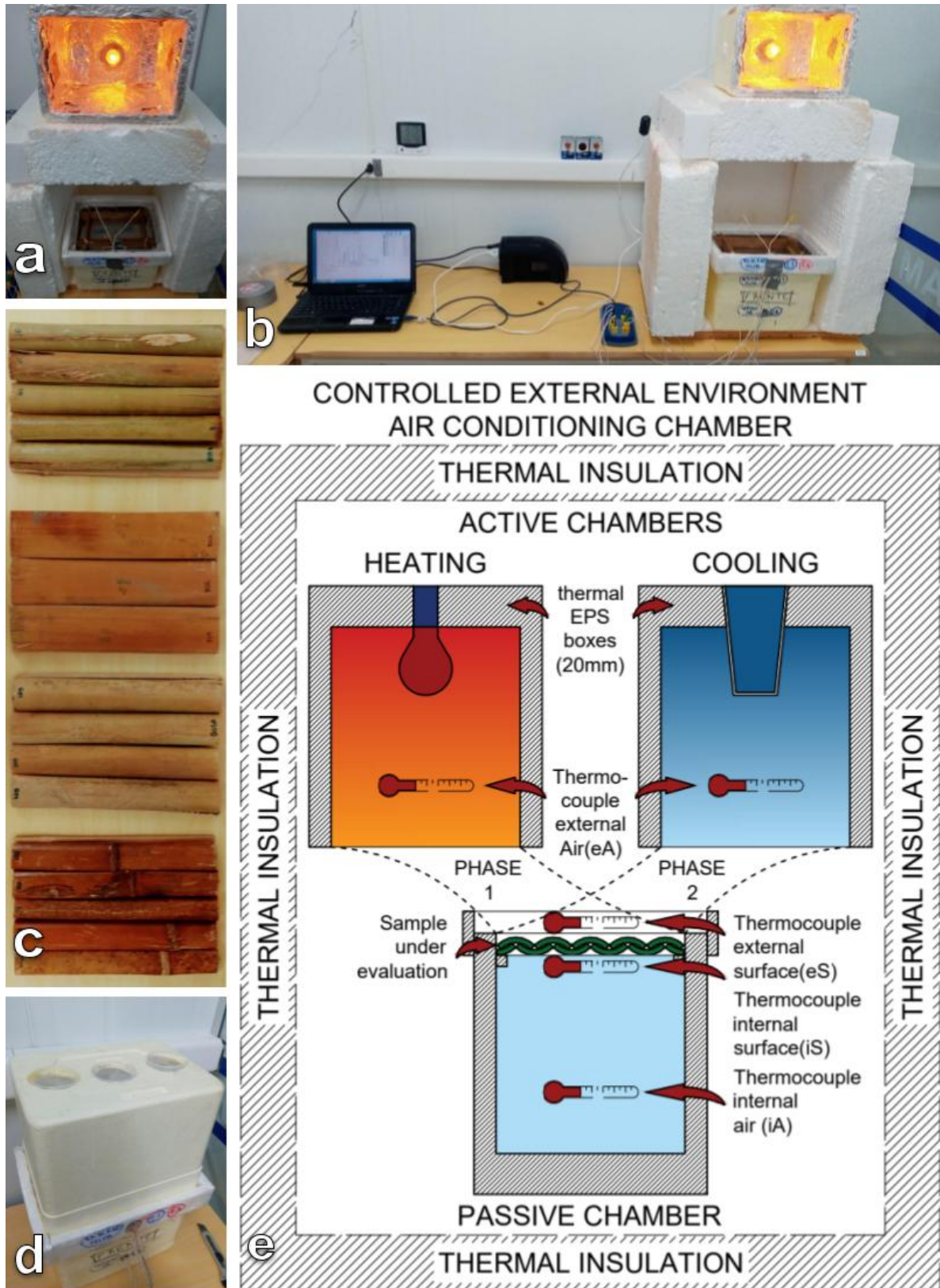
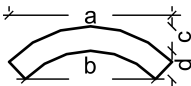
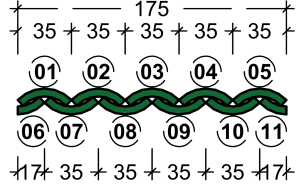
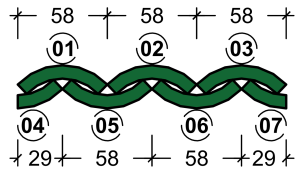
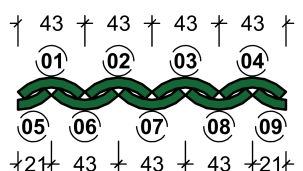
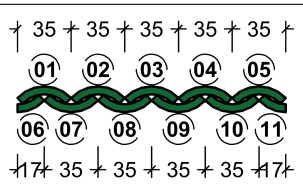


Figure 4: (a) Visualization of the sample positioned for analysis with the activated chamber. (b) Complete setup of the hotbox and the four groups of samples from the different species (c). Setup for phase 2, cooling, with the chamber containing ice containers (d). (e) Schematic diagram of the Hot Box setup with the location of the thermocouples.

Table 4

Morphology, designation, organization, and dimensions of the samples as placed at the "hotbox" setup.

Species	Cross-sectional diagram and sample organization	
Average dimensions (mm)		
<i>Bambusa tuldoidea</i>		a=35; b=25; c=05; d=07
<i>Dendrocalamus giganteus</i>		a=58; b=50; c=08; d=07
<i>Guadua augustifolia</i>		a=43; b=30; c=06 d=10
<i>Phyllostachys aurea</i>		a=35; b=25; c=05; d=07

application to ensure accurate data recording (data collection frequency, designations, etc.). Subsequently, the incandescent lamp is activated, initiating the temperature increase in the system, referred to as "Phase 1". The room where the experiment was conducted was climate-controlled at a temperature of approximately 19°C, significantly below the PCM's melting point. Therefore, the active box setup needed to elevate the temperature above 24°C but not significantly beyond 40°C to avoid a substantial deviation from the ambient climate. This choice determined the power of the heating element. To accelerate the test stage in which the behavior of the sample is measured when the temperature decreases (phase 2 or cooling), an extra active chamber was added for this purpose using containers (with controlled volume) containing ice as shown in figure 4d.

Phase 1 (heating) of the experiment, focused on temperature increase, started with the lamp activation when the system was all around 19°C. The temperature in the active chamber was raised to values exceeding 40°C, and then the temperature rise gradually decreased, as observed by the thermocouples in both the active and passive chambers. This indicated the stabilization of the system with the energy source activated a process that took 90 minutes. In Phase 2

(cooling), involving temperature decrease, the active chamber, which contributed heat, was turned off and separated from the passive chamber was replaced by the box with ice containers. This allows a rapid temperature reduction to the setup temperature. Gradually, the influence of the barrier/sample on this cooling process was also noted. This temperature reduction and stabilization process took also 90 minutes.

The thermocouples in the thermal box system were positioned at four levels (fig. 4e), with duplicates, to guarantee the reliability of the collected data. The frequency of temperature recording was every 15s and they were arranged as follows:

- External Air (eA) thermocouple: positioned at the geometric center of the active chamber's volume.
- External Surface of the sample (eS) thermocouple: placed on the surface exposed to the environment of the active chamber of the evaluated barrier.
- Internal Surface of the sample (iS) thermocouple: placed on the surface exposed to the environment of the passive chamber of the evaluated barrier.

- Internal Air (iA) thermocouple: positioned at the geometric center of the volume of the passive chamber.

2.4. Complementary characterization - microscopy and ultrastructural analysis

In order to proceed an anatomical examination of the plant structures, allowing observation of tissue patterns, vascular structures, and porosity, light optical microscopy was used as well as the following instruments: Stereomicroscope with epifluorescence SMZ 1500 (Nikon), Confocal Microscope LSM 780 (Carl Zeiss) and Ultra-high-resolution Field Emission Scanning Electron Microscope - STEM - CLARA model. To observe internodal regions, and cross-sectional cuts to capture images of the stalks Krause (2015) ; Júnior (2012). These samples, measuring approximately 10 mm x 5 mm x 5 mm, were derived from bamboo strips and placed in molds for embedding. Subsequently, the blocks underwent vacuum impregnation with embedding epoxy resin (Epoxy) from the Struers brand. The blocks were sanded using a sequence of progressively finer grits on an orbital sander and subsequently polished with diamond paste on an orbital polisher. This procedure was carried out at the Centro de Tecnologia Mineral (CETEM-UFRJ) Krause (2015); Krause, de Andrade Silva, Ghavami, Gomes and Filho (2016).

2.5. Chemical characterization

For thermal analysis through thermogravimetry (TGA), which aimed to confirm the chemical composition of the samples, a TGA Q500 TA Instruments thermal analyzer (Delaware, USA) was used, set with a heating rate of 10°C/min. Between 7 and 10 mg of powdered sample were placed in the crucible and heated from 25 to 1000°C. The analysis conditions included a synthetic air atmosphere (80% N₂ and 20% O₂) flowing at a rate of 60 mL/min Raabe, Fonseca, Bufalino, Ribeiro, Martins, Marconcini, Mendes and Tonoli (2015). Critical temperatures for mass loss, including the initial temperature, the temperature range within which losses between 70% and 80% of the sample mass occurred (shoulder temperature), and the temperature at which the final mass stabilized (final temperature), were determined through examination of the TG and derivative TG curves.

Fourier-transform infrared spectroscopy (FTIR), vibrational infrared spectroscopy analyses were performed using a Varian 600-IR Fourier-transform infrared (FTIR) spectrometer equipped with a Pike Technologies GladiATR accessory for attenuated total reflectance (ATR) measurements at a 45° angle, utilizing a zinc selenide crystal. The spectral range analyzed was from 400 to 4,000 cm⁻¹, with a resolution of 2 cm⁻¹ and 32 scans.

For chemical analyses, the samples were processed into a homogeneous form consisting of powder or fine grains of the samples. This approach ensured consistency in the analytical procedures.

Table 5

Location and acronyms of the thermocouples used in the experiment as shown in fig. 4e.

Location	Acronyms
External Air	eA
External Surface of sample	eS
Internal Surface of sample	iS
Internal Air	iA

3. Results and discussion

3.1. Basic characterization

The data presented in Figure 5 reveal that with the samples previously dried in an oven, the impregnation index achieved was always above 7.76%, even in the bamboo species with the highest density (*Phillostachys aurea*). This index is higher than what was achieved with the impregnation method using the solid culm without immersion (7.11%) Fontenelle et al. (2023); Fontenelle and Ferreira (2024). Impregnation reached above 14,88% in the species with lower density (*Dendrocalamus giganteus* and *Guadua augustifolia*), demonstrating a direct correlation between density and impregnation content.

3.2. Hotbox test

The results of the thermal tests are depicted in Figures 6, 7, 8 and 9, illustrating temperature profiles recorded by the thermocouples positioned within the setup, as detailed in Table 5 as well as the subtraction between the antagonistic positions of the present thermocouples. The samples underwent thermal testing encompassing both heating and cooling cycles (phases 1 and 2).

The results were presented individually for each species in the three proposed treatments (Fig. 6) and combined for better data comparison visualization (Fig. 7). The solid, dashed and dotted lines represent respectively the analysis 2 (PCM), analysis 1 (PU) and the control (raw) samples. Each color represents the average measurement of a pair of thermocouples positioned simultaneously in the regions as described in table 4, with eA, eS, iS and iA respectively in red, green, cyan and blue colors, it is also possible to distinguish each species by its specific symbol as shown in the lines.

The results presented in Figure 6 show that the temperature variation profile in all thermocouples of the control samples and those resin-coated with PU are quite similar. Similarly, in both samples, the temperatures of the external air (eA) and the external surface (eS) of the sample rose rapidly due to the heat emitted by the lamp. However, there is a significant delay in heating the sample's internal surface (iS) and even more so in the interior air (iA) of the passive chamber in the same samples. This delay is, however, much more pronounced when we look at the curve of the sample treated with PCM, highlighting that even the external surface (eS) of the PCM-treated sample experiences a slight delay in

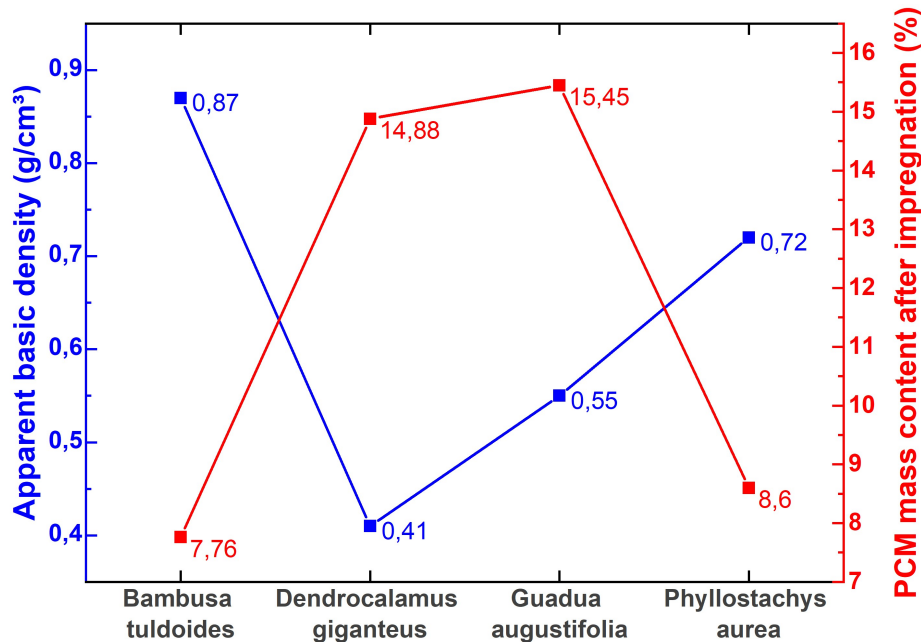


Figure 5: Graph containing the results obtained for apparent basic density and PCM impregnation content.

temperature increase as shown and pointed by red arrows at the amplified graphs in figure 7.

A comparison between the PU and control samples shows that the temperature of the resin-coated samples with PU was slightly lower in all thermocouples except for the sample of the species *Bambusa tuldoidea*. However, there is no visual evidence of a change in the temperature growth trend, as the curves exhibit a constant linear trend, with parallelism between the treatments. This suggests a very similar heat transfer with these two treatments.

A comparison between the PCM and the other two treatment samples however notably, when the PCM-impregnated sample reaches approximately 24°C, the curve trends begin to shift. This shift coincides with the PCM undergoing a phase change, absorbing heat, and consequently delaying the temperature increase. For instance, while the internal surface thermocouple of the non-impregnated samples (iS PU and iS Ctrl) takes approximately between 20-30 minutes to reach 25°C, the PCM-impregnated sample (iS PCM) requires approximately between 40-50 minutes, indicating a relevant longer time to reach the same temperature. This result demonstrates the efficacy of PCM-impregnated bamboo culms for thermal energy storage where there is visibly an action by the PCM in anchoring the temperature change of physical state for both heating and cooling, respectively, around 24°C and 21 °C (fig 8d).

When the analysis, as shown in Figure 8, compares the bamboo species used in the treatments, a fairly similar behavior is observed among them with equivalent curves. However, it is possible to highlight a slightly more efficient characteristic regarding the temperature anchoring related to the phase change of the PCM in the sample of *Dendrocalamus giganteus* species. It showed a quantitatively

higher impregnation content (14,88%), and its samples have substantially thicker dimensions (8mm) compared to the other three species studied, which with this combination of factors could explain such behavior.

Quantitatively, we can also observe that, for example, when the *Dendrocalamus giganteus* sample PCM impregnated on the interior surface thermocouple (D iS PCM), as shown in Figure 8c, reaches around 25°C, it takes approximately 53 minutes from the activation of heating. For the other impregnated species, this happens at 45, 43 and 41 minutes post activation (respectively for species P, B and G), thus practically 10 minutes earlier, suggesting a delay of about 20% superior to other samples subjected to identical treatment.

To emphasize the efficiency of the PCM, it's worth noting that for the same species of bamboo (D.), the delay in the thermocouple on the inner surface (iS) between the impregnated bamboo and the bamboo only resin-coated with PU (31 minutes post activation) is 22 minutes, representing a substantial delay of about 41%. In the other studied species, this delay between the internal surface (iS) between samples with PCM and PU reaches around 20, 18 and 16 minutes (respectively for species P, B and G), once again demarcating the expressiveness of storage of thermal energy

The results that can be observed in Figure 9 also demonstrate analyses conducted regarding the temperature difference ($\delta T^{\circ}\text{C}$) between the profiles measured for the external air as opposed to the internal air (iA-eA) in red, which evidently represent the largest variations found. Additionally, the differences between the temperatures measured on the external surface and the internal surface (iS-eS) highlight the delay in conduction and the storage of thermal energy through the samples.

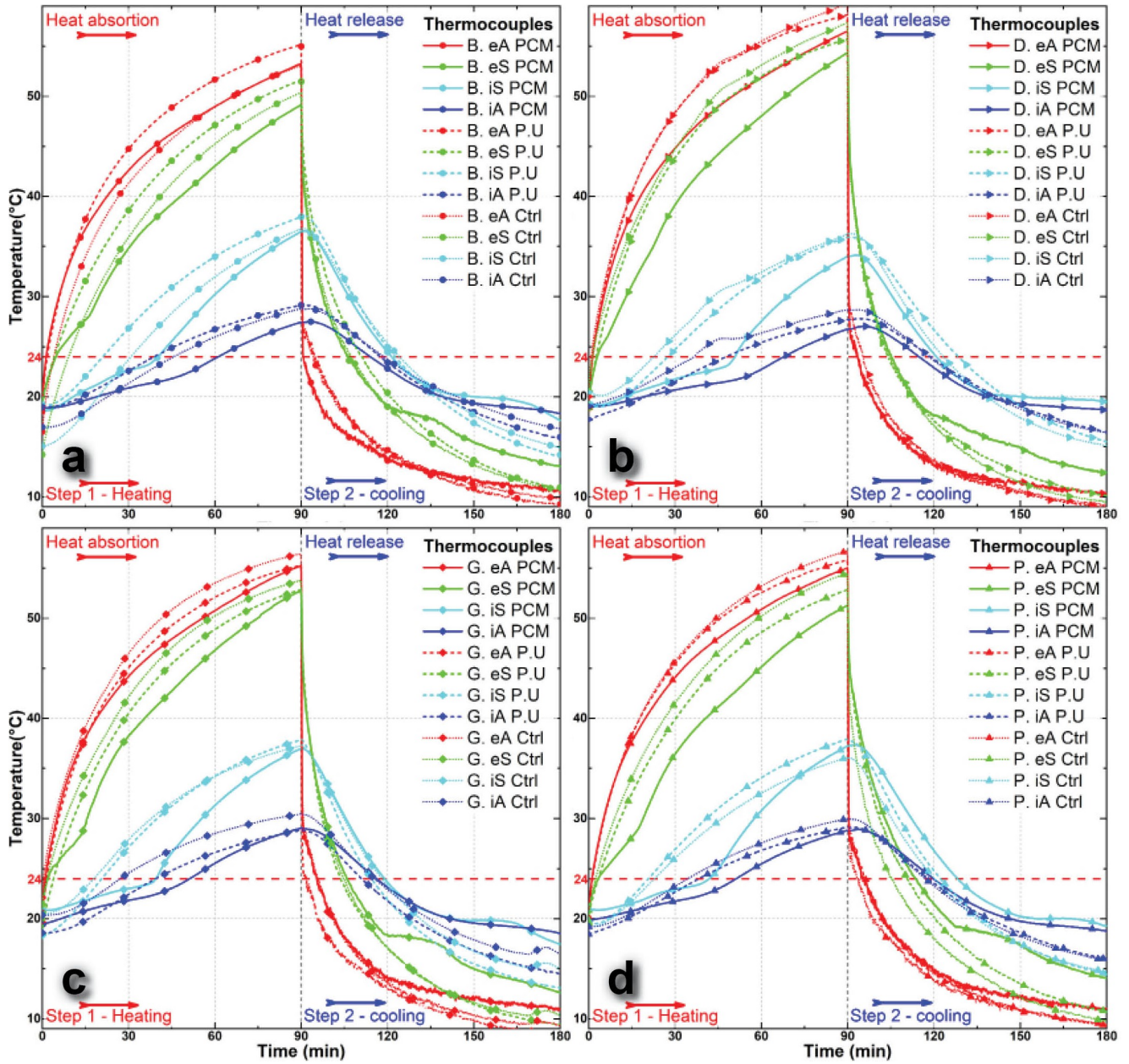


Figure 6: Temperature profiles for the thermocouples at the hotbox experiment for *Bambusa tuldoidea* (a), *Dendrocalamus giganteus* (b), *Guadua augustifolia* (c) and *Phyllostachys aurea* (d) samples submitted to the control (Ctrl), resin-coated with polyurethane (PU), and PCM impregnated treatments.

Observing the results shown in figure 9 and 10, it's possible to notice a greater difference occurring between the internal air and the external air in all cases, as well as a tendency for the difference to stabilize when the temperature emitted by the lamp stabilizes, always around the 75 min. A larger difference is also evident in the *Dendrocalamus giganteus* samples, both in terms of the difference between the internal and external surfaces and between the internal and external air. It is also possible to observe a similar increase in the difference in the PU resin samples compared to the raw bamboo culm samples.

Regarding the samples treated with PCM (fig. 9c, d and e), there is also a clear distortion in the graph profile starting

after the 30th minute of the experiment, where small peaks can be observed. These peaks are also noticeable during the second phase of the experiment, where the external air temperature becomes lower than the internal air temperature around the 140th minute. These peaks are likely caused by the action of the PCM, which anchors the temperature due to the storage of thermal energy, either absorbing or releasing heat. In these peaks, in the heating phase, for example, differences can be measured between the temperatures of the internal and external surface of the sample (iS-eS) of the order of 21.98, 17.24, 16.36 and 14.07 °C (respectively in species D, G, P and B, while the samples sealed with PU

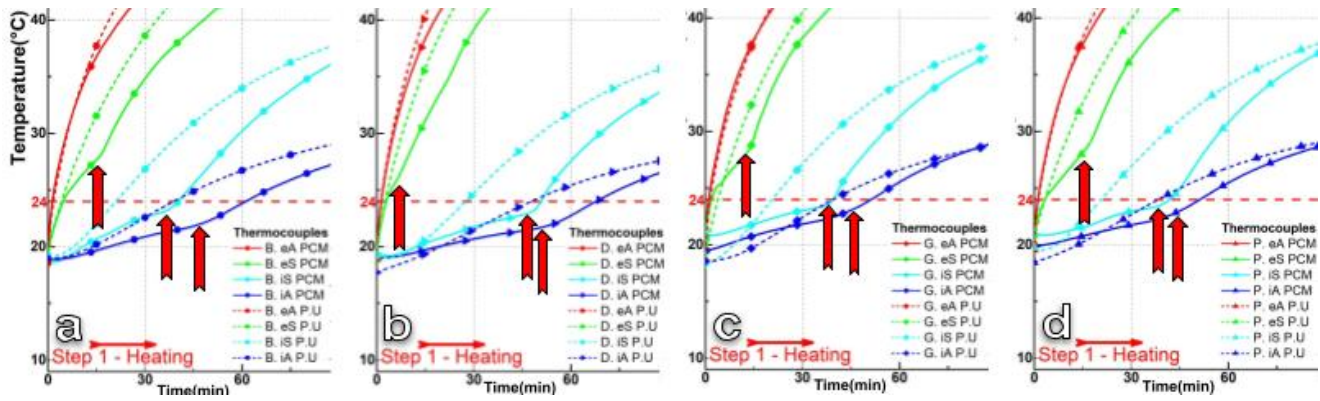


Figure 7: Amplified temperature profiles *Bambusa tuldoidea* (a), *Dendrocalamus giganteus* (b), *Guadua augustifolia* (c) and *Phyllostachys aurea* (d) samples submitted to the control (Ctrl), resin-coated with PU (PU), and PCM impregnated treatments with the anchorage sections caused by thermal energy storage highlighted by red arrows.

obtained maximum deltas of 20.37, 14.92, 14.78 and 13.67 °C (D, G, P and B respectively).

3.3. Microscopy and Ultrastructural Analysis

Under 10x magnification, as depicted in Figure 11, it is possible to discern and delineate the anatomical structures that make up bamboo, along with the high content of voids at various scales. Notably, larger voids are observable within the sap-conducting vessels within the parenchyma, a structure primarily constituted of lignin that forms the cellular framework. In Figures 11 a-d, these voids are impregnated with solid-state PCM, imparting a waxy appearance, a phenomenon absent in Figures 11 e-l, where the raw bamboo stalk remains in its natural state, rendering the sap-conducting vessels as distinct dark polygonal shapes. Figures 11 i-l with a 125x magnification, it is possible to observe a more detailed view, including the bundle of sap-conducting vessels with more pronounced voids, as well as intercellular and intracellular spaces of the raw bamboo culm.

Figure 12 presents a sequence of timed images, captured at 20 second intervals, on a 10x scale. These images document the melting and subsequent release of PCM impregnated within bamboo when subjected to temperatures exceeding 24°C, its melting point. It is important to note that this leakage is exclusively observable in the cross-sectional cut section of bamboo, emphasizing the potential loss in the absence of PU resin sealing in this area.

Figure 13 offers a series of sequential images on a macroscopic scale, also captured in a time-lapse format, showcasing the process of impregnation with an aqueous-based dye within a cross-section of *Phyllostachys aurea* (P.) that had been previously oven-dried without vacuum application. These images illustrate the rapid absorption of the liquid by the porous bamboo structure.

In figure 14 images obtained by MEV it is possible to observe, on a comparative scale, the large voids present in the anatomical microstructure of bamboo plant tissues and in Figure 15, we observe the scanning of the cross-sectional surface of the bamboo culms performed using the

confocal microscope, with an assessment of its roughness. Both the three-dimensional image and the surface profile of the section demonstrate how rough it is.

3.4. Chemical characterization

Figure 16 presents the thermogravimetry (TG) and derivative thermogravimetry (DTG) curves, offering insights into the chemical composition of the samples which were extracted from the same used in the hotbox essay adding up a sample of raw polyurethane resin (PU). Generally, the initial mass loss, observed up to 100°C, arises from the release of free water (except in PU) (fig.16b) within the material during the early moments Guimarães (2023) Further mass loss events are discernible in these curves, including:

- In the raw bamboo sample (control)(fig.16c), an initial peak is noticeable, occurring roughly between 250 and 320°C, corresponding to the degradation of hemicellulose (typically between 150 and 350°C Kim, Kim, Kim and Yang (2006). Subsequently, a sharp peak centered at 348°C corresponds to the degradation of cellulose. Finally, a lower-intensity peak, slightly above 400°C, likely corresponds to the degradation of lignin, typically occurring within the range of 250 to 600°C, all constituents found in substantial proportions in the vegetative tissues of the examined bamboo species which are visible in all analyzes shown.
- In the PCM-treated sample curve (fig.16a), a peak emerges shortly after 200°C, distinguishing it from samples treated without PCM. This disparity results from the degradation of PCM, an organic ester, begins at relatively low temperatures Poletto, Ornaghi and Zattera (2014) with a center around 234°C. These samples also exhibit corresponding peaks akin to those observed in natural samples of these plant tissues.
- Regarding the sample treated only with PU resin (fig. 16b), it's essential to consider that, according

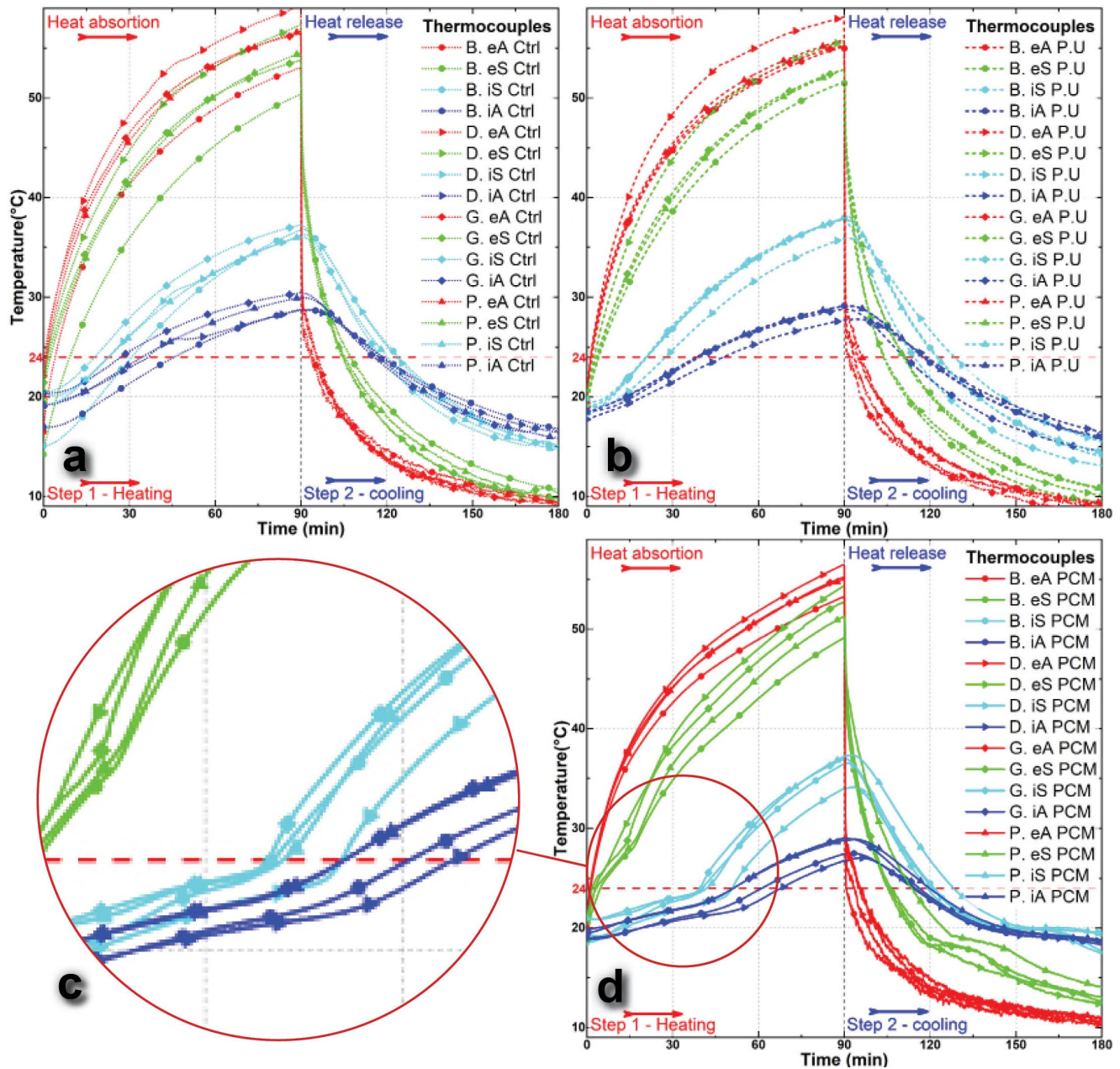


Figure 8: Temperature profiles for the samples submitted to the control (a), resin-coated with PU (b), and PCM impregnated (d) treatments of the four tested species and a zoom focused on the profile distortion (bounded by the red circumference) caused by the operation (thermal energy storage) of the PCM (c)

to literature sources Azevedo, Santana, Nascimento, Claro Neto and Lepienski (2009); Müller, Rubio-Pérez, Bach, Muñoz-Rujas, Aguilar and Worlitschek (2020), polyurethane undergoes mass loss in two decomposition stages. The first stage starts at 240°C and ends at 350°C, related to the rupture of urethane bonds. The second stage starts at 500°C, pertains to the decomposition of ester bonds within the polyol. These peaks are discernible despite potential overlap with hemicellulose degradation occurring at similar temperatures especially if compared to the raw PU profile presented.

- The samples shown in fig. 16d were included in the analysis to highlight any visible difference in the impregnation of the anatomical tissues present in the walls of the internodes of bamboo culms and *Dendrocalamus giganteus* culm was used. There is a substantial variation in vascularity and, consequently, porosity between the innermost parts of bamboo walls and their parts closer to the outer limit. In this case, the samples were precisely taken from the inner third and the outer third, excluding the intermediate third. What can be observed is that the most prominent peak is located between 200°C and 300°C, with the peak

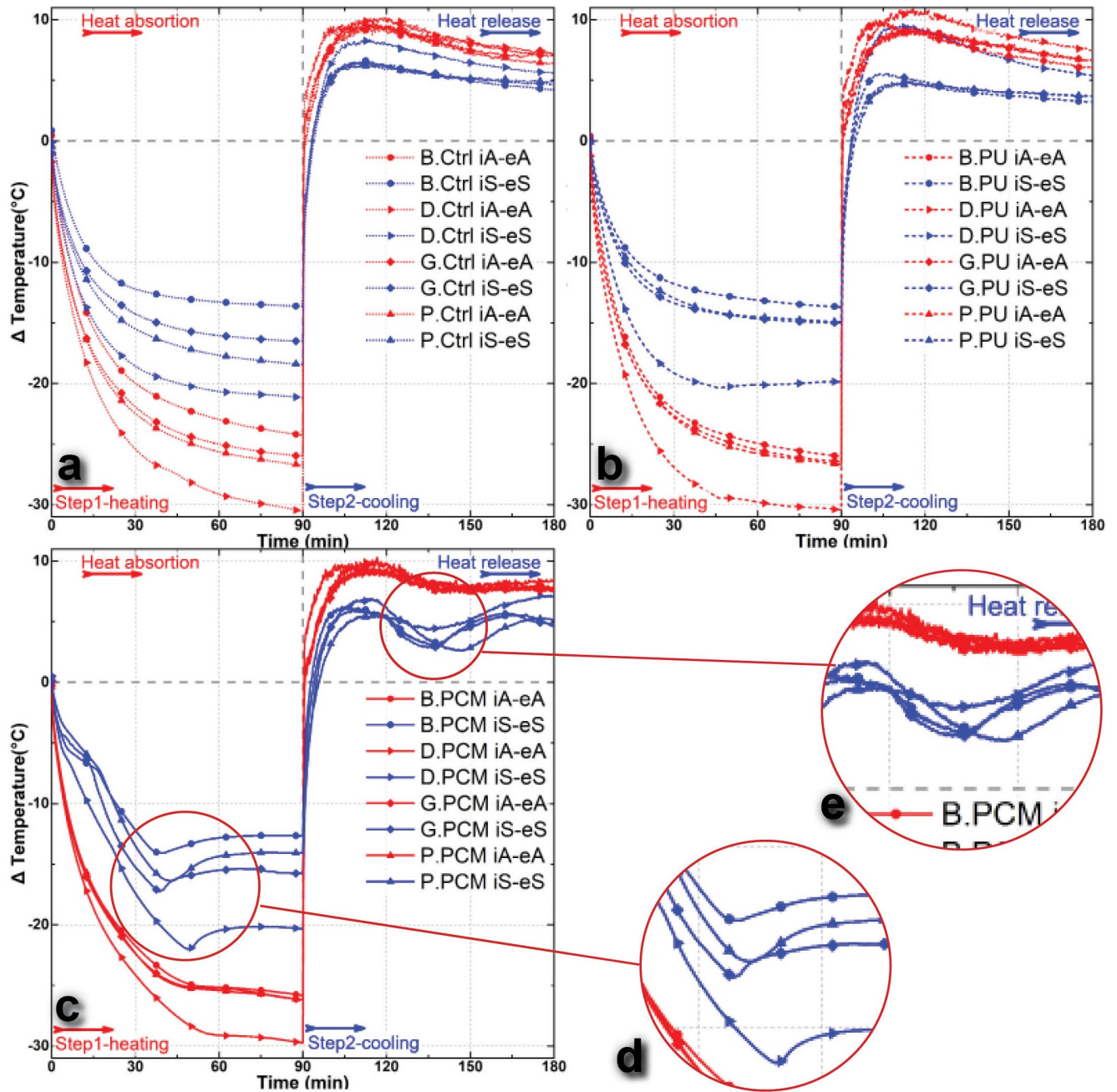


Figure 9: Temperature profiles for differences between the external air minus the internal air (iA-eA), and the external surface minus the internal surface (iS-eS). Control sample (a), resin-coated with PU (b), and PCM impregnated (c) treatments and two zooms (d and e) focused on the profile distortion (bounded by the red circumferences) caused by the operation (thermal energy storage) of the PCM.

following it, which in other samples corresponds to the constituents of plant tissue, but is diminished. The observed variations demonstrate changes in the proportion of material components in these two different layers, but only a very subtle difference is observed in the degradation temperature of the PCM, which does not allow for a clear visibility of variations in the quantity of this substance.

Regarding the samples shown in fig.17, organized by species, it's possible to observe more clearly the influence

of the treatment in each analysis by the peaks related to the PCM and PU degradation.

These results help to confirm the presence of PCM in the samples and underscore the efficacy of the proposed method for PCM incorporation into bamboo culms.

Fourier Transform Infrared Spectroscopy (FTIR) was employed for identifying functional groups, primarily in vegetal fibers Rodrigues and Galzerani (2012), and chemical bonds in materials. The used samples were the same as the TG essay adding up raw PCM. The result is obtained

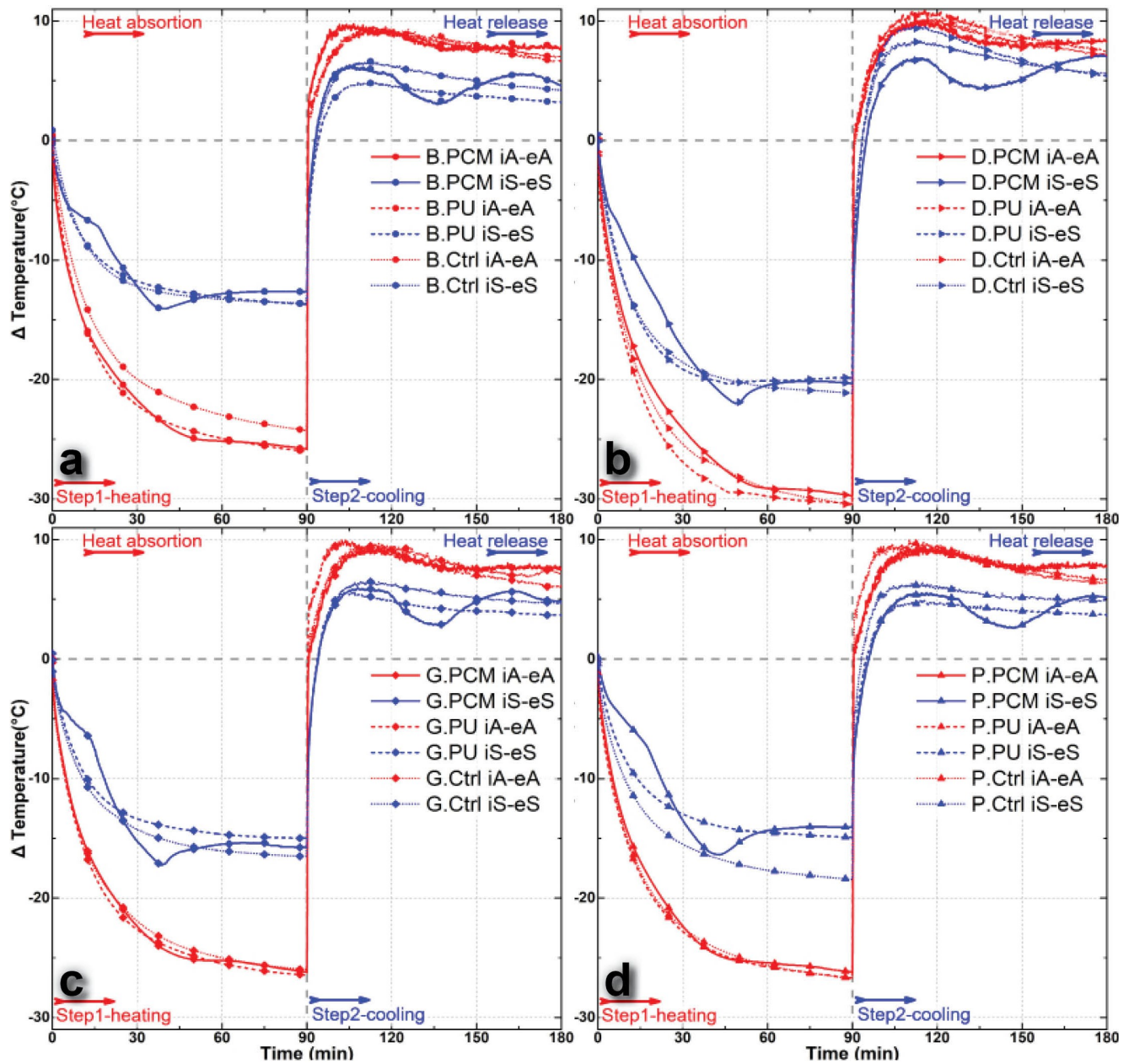


Figure 10: Temperature profiles for differences between the external air minus the internal air (iA-eA), and the external surface minus the internal surface (iS-eS) of the *Bambusa tuldoidea* (a), *Dendrocalamus giganteus* (b), *Guadua augustifolia* (c) and *Phyllostachys aurea* species (d).

from the absorption of radiation at various wavelengths in scans ranging from 4000 to 500 cm^{-1} Fredericci, Ferreira, Oliveira and Pinto (2016), as observed in the results shown in Figure 18. The active peaks obtained in all bamboo samples exhibit a remarkable degree of similarity, suggesting minor variations in intensity. Existing literature suggests that for each absorbance band, there are peaks associated with characteristic chemical functional groups in specific materials, including lignocellulosic substances Sánchez Vivas et al. (2019).

The primary chemical elements within bamboo encompass lignin, cellulose, hemicellulose, starch, silica, and

pectin. According to Liu and Fei (2013) the bands between 1600 and 1450 cm^{-1} correspond to the characteristic region of lignin, hemicellulose, cellulose, and pectin, with peaks between 1558 and 1508 cm^{-1} indicating the presence of lignin, as well as peaks between 3338 and 1234 cm^{-1} .

Around 3000 cm^{-1} , low-intensity peaks are observed in sample treated with PCM, related to the stretching of =C-H bonds in alkenes. These bonds exist in the polymers due to the butadiene monomer Guimarães et al. (2023) Two peaks can be observed at 2919 and 2850 cm^{-1} , related to the stretching of C-H bonds in alkanes. These bonds are, present in bamboo fiber components (cellulose, hemicellulose, and

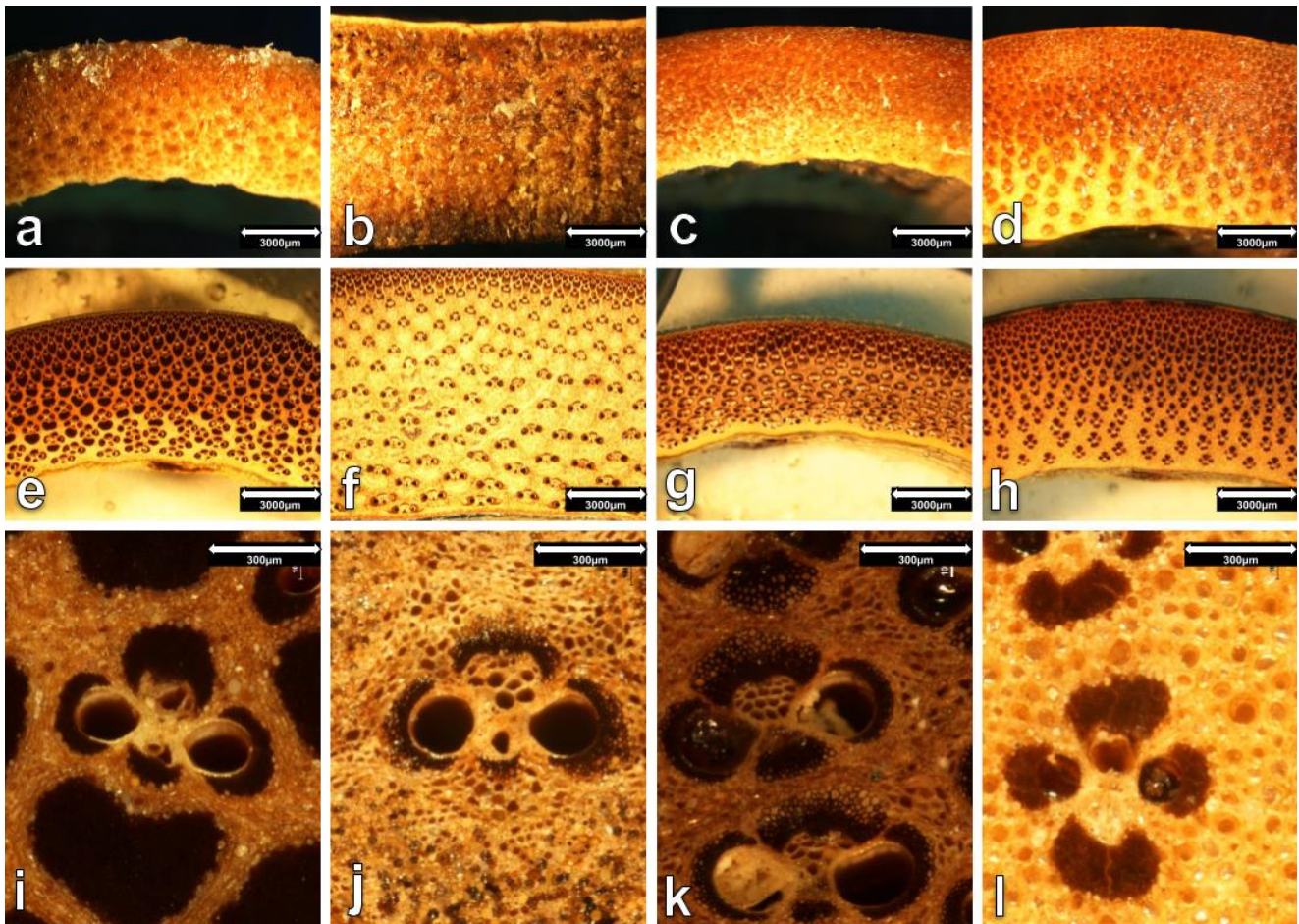


Figure 11: Images obtained by Stereomicroscope (at 10x magnification (a-h) and 125x magnification (i-l)) of the internodal cross-sections of *Bambusa tuldoidea* (a, e and i), *Dendrocalamus giganteus* (b, f and j), *Guadua augustifolia* (c, g and k) and *Phyllostachys aurea* (d, h and l) bamboo culms with PCM impregnation (a-d) and without impregnation (e-h), and an images at 125x magnification of the same transversal cut of the mid part (i-l) of the culm wall.

lignin) and soluble extractives, as well as in the polyurethane resin (PU) polymer structure, resulting in an increase in the intensity of these peaks in treated samples.

A peak is also observed at 1735 cm^{-1} , ascribed to the stretching of C=O bonds. This peak is attributed to the acetyl ester and uronic acid groups in hemicelluloses or the ester linkage of ferulic and p-coumaric acid groups in lignin and/or hemicellulose Ferreira, Silva, Lima and Toledo Filho (2017). An increase in the intensity of these peaks is observed in sample without PCM, probably due to the C=O bonds of polymer carboxylic groups. However, in sample containing PCM, these peaks tend to decrease in intensity and shift slightly, possibly due to interactions between the PCM and C=O groups present in bamboo components Guimarães (2023).

In the region between 1300 and 1000 cm^{-1} , some peaks related to the stretching of C-O bonds can be observed, characteristic of alcohol, carboxylic acids, ester functional groups, or ethers present in bamboo fiber components or PU polymer. In the range between 1220 and 1133 cm^{-1} , there was a decrease in peak intensity in PCM containing

sample, presumably related to interactions between PCM and bamboo or polyurethane components.

The 900 and 896 cm^{-1} peaks can be attributed to β -glycosidic linkages between xylulose units in hemicellulose. The bands between 1458 and 1373 cm^{-1} may be indicative of typical cellulose absorption. The 1630 and 1639 cm^{-1} peaks are attributed to stretching vibration of vibrations, signifying the presence of starch and H₂O, respectively Pedrangelo (2020).

According to Liew, Hamdan, Rahman, Rusop, Lai, Hossen and Rahman (2015), the band from 3200 to 3500 cm^{-1} (3338 cm^{-1}) usually indicates an increase in hydroxyl groups, and the 2921 cm^{-1} peak indicates polysaccharide CH. The 561 cm^{-1} peak indicates the presence of CBr. The 1735 cm^{-1} peak indicates the C=O bond. These findings collectively provide valuable insights into the chemical composition and structural attributes of the investigated bamboo samples and reveal that no significant chemical reactions occur during the impregnation process.

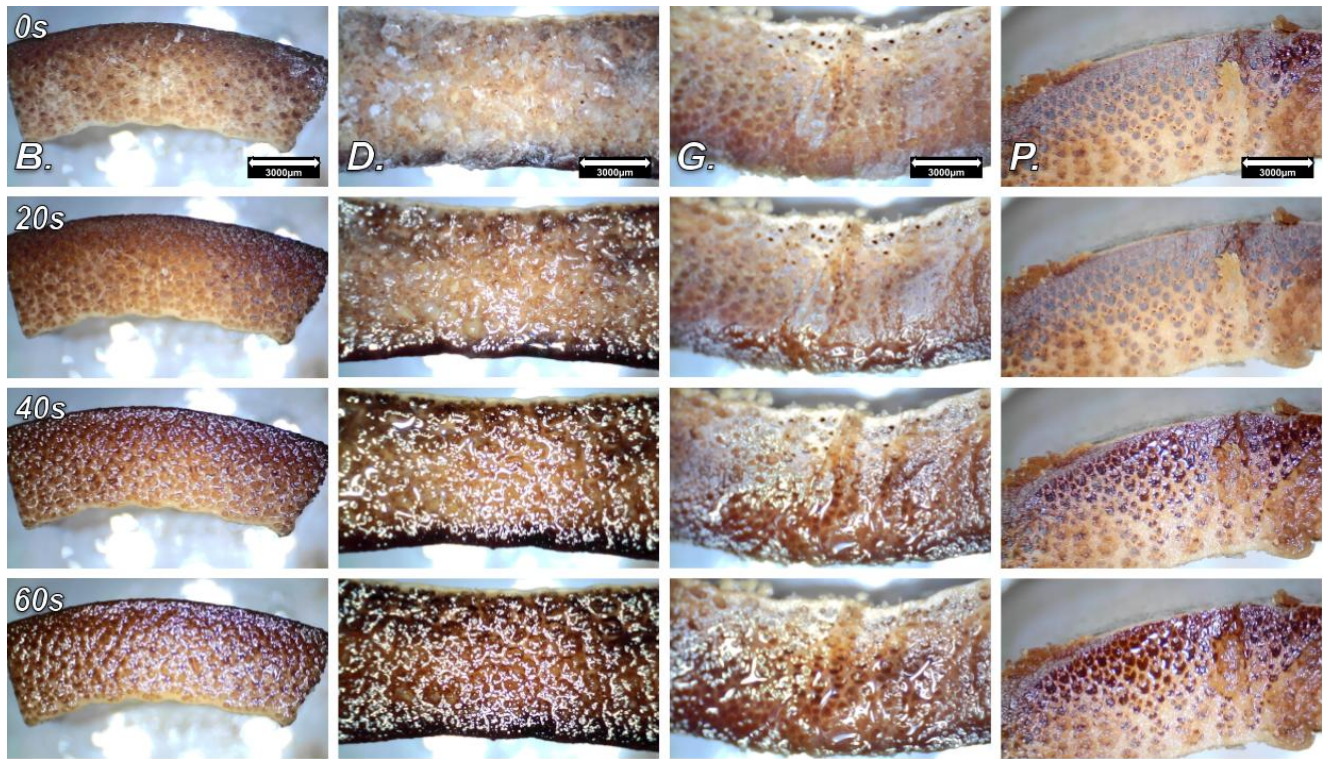


Figure 12: Successive images at 10x magnification extracted from the melting process of PCM impregnated of *Bambusa tuldoidea* (B.), *Dendrocalamus giganteus* (D.), *Guadua augustifolia* (G.) and *Phyllostachys aurea* (P.) bamboo culms, taken every 20 seconds.

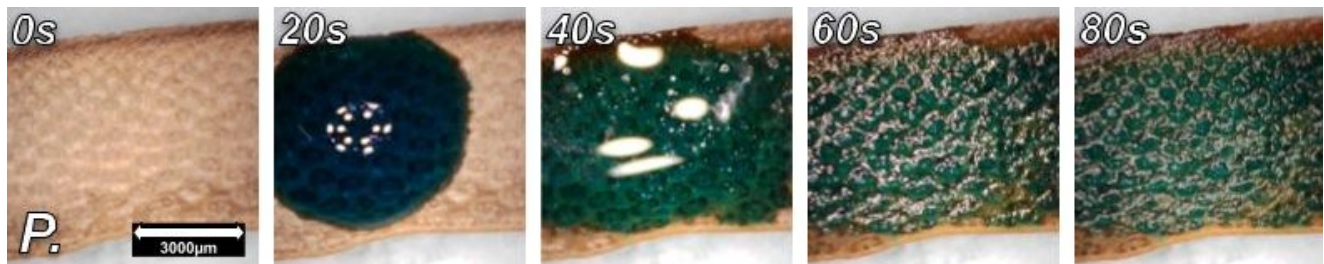


Figure 13: Successive images on a macroscopic scale of the bamboo *Phyllostachys aurea* dye impregnation process, chronologically taken every 20 seconds.

4. Conclusions

This study presents a straightforward process for utilizing bamboo culms as a supportive matrix for phase change materials (PCMs). Bamboo culms are impregnated using negative pressure while in their usual practical use shape, and sealed with polyurethane resin to create a thermally efficient composite material. Thermal analysis demonstrated the material's ability to anchor temperature around the specific PCM melting point (24°C), highlighting its functionality.

Moreover, FTIR, TG, and DTG analyses reveal that no significant chemical reactions occur during the impregnation process, which is beneficial for its application in phase change thermal energy storage applications. This process ensures the PCM efficiently penetrates the porous structure of the bamboo culms. As a result, the developed composite

material holds promise as a versatile bamboo-based composite material that combines multiple functions and has the potential for development in energy-saving applications related to building thermal conditioning. It is expected to enhance the energy efficiency of buildings and other related purposes.

The results of this work also demonstrate that it is advisable to conduct a more in-depth analysis of the possibilities of impregnating bamboo culms with PCM. Other species with specific characteristics may likely have more interesting capabilities for this application, as well as other impregnation methodologies and thermal analysis techniques that can be evaluated for process improvement.

Dendrocalamus giganteus species with larger dimensions in terms of wall thickness, distance between nodes, and culm diameter and length, along with lower density,

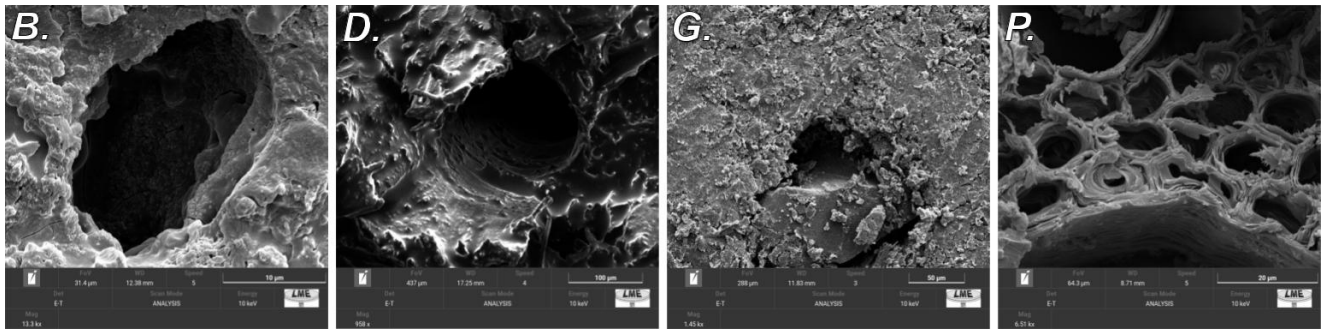


Figure 14: Images obtained by Ultra-high-resolution field emission scanning electron microscope (MEV) of the internodal cross-sections B., D., G. and P. species.

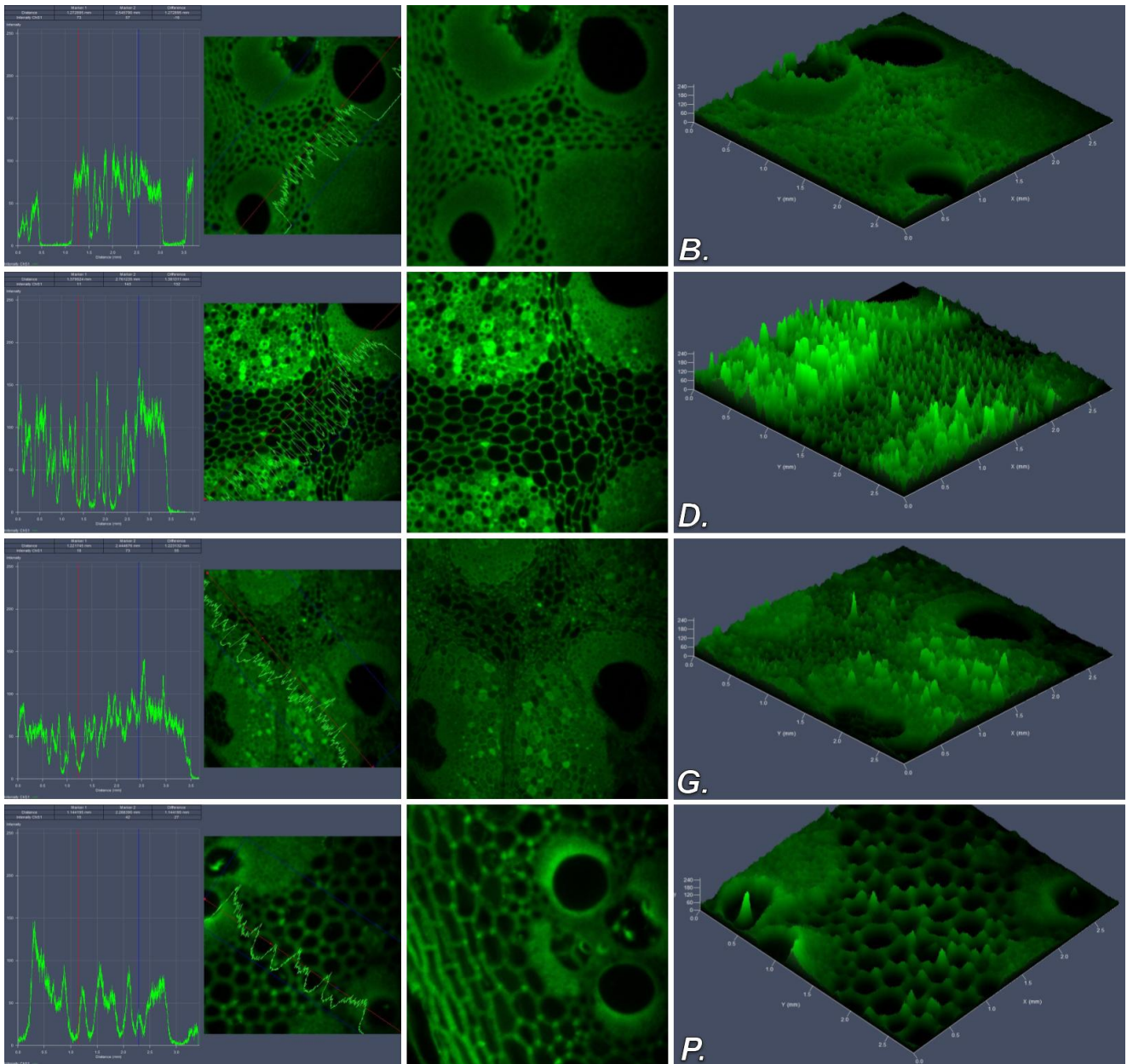


Figure 15: Images obtained by Confocal Microscope of the internodal cross-sections B., D., G. and P. species.

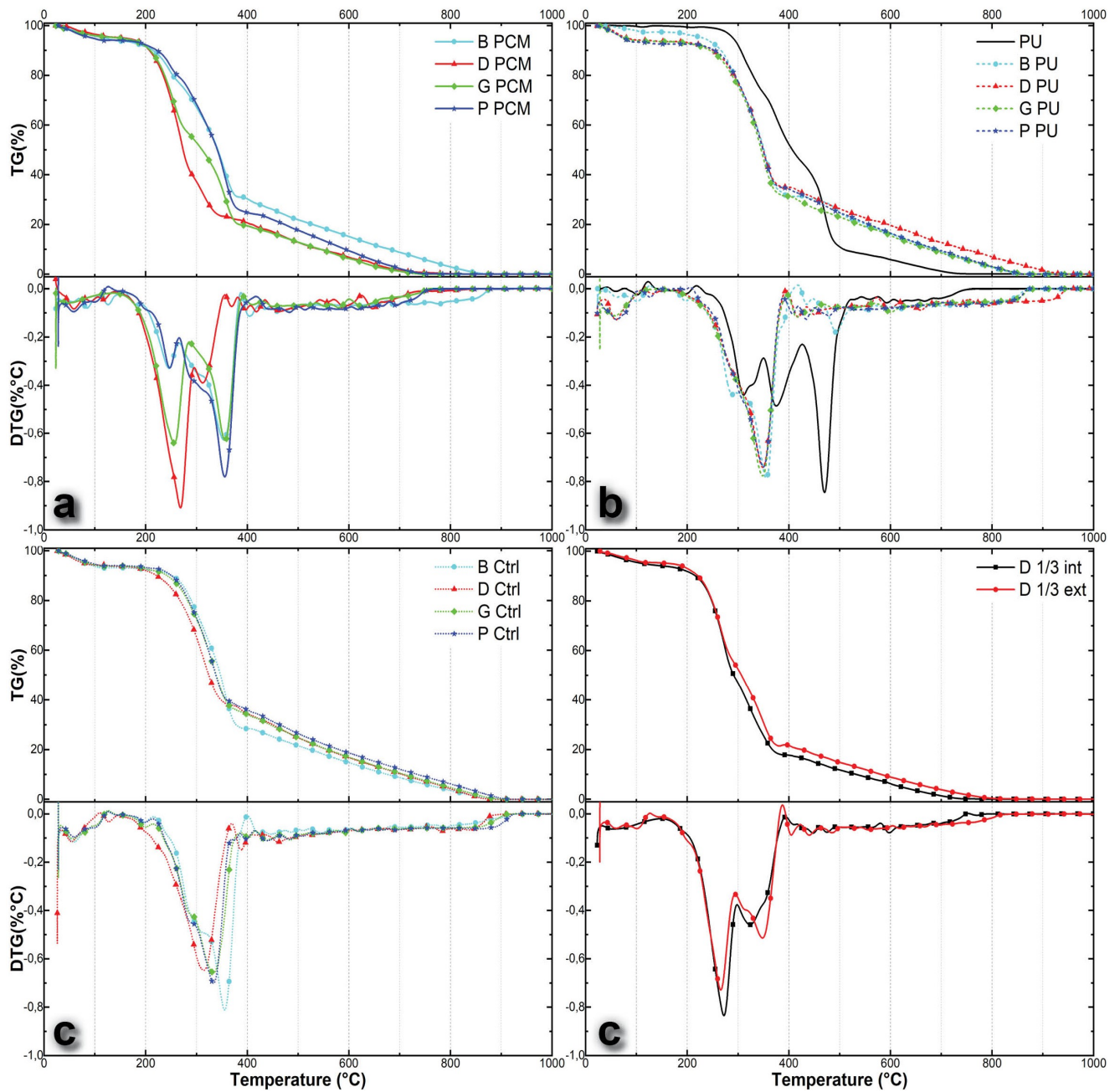


Figure 16: Thermogravimetric analysis curves, TG and DTG for Control(a), resin-coated with PU (b), and PCM impregnated (c) samples of the four investigated species, and (d) inner (internal) and the outer (external) third of bamboo walls.

exhibited greater efficiency for the desired purposes demonstrating a significant temperature anchoring compared to the other species and had a higher PCM impregnation content in a larger volume of material, making it, at first, the best-qualified species among those studied.

The relationship between the prior density of bamboo culms and their impregnation capacity was confirmed in this experimental campaign and the methodology for the impregnation was also improved by an immersion process in an environment subjected to negative pressure through vacuum pumping, resulting in a higher PCM content in the samples.

CRediT authorship contribution statement

Fabício Rezende Fontenelle: Conceptualization, Methodology, Data curation, Visualization, Writing original..

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A comparative study of four different species bamboo culms as a carrier for thermal energy storage through phase change material impregnation

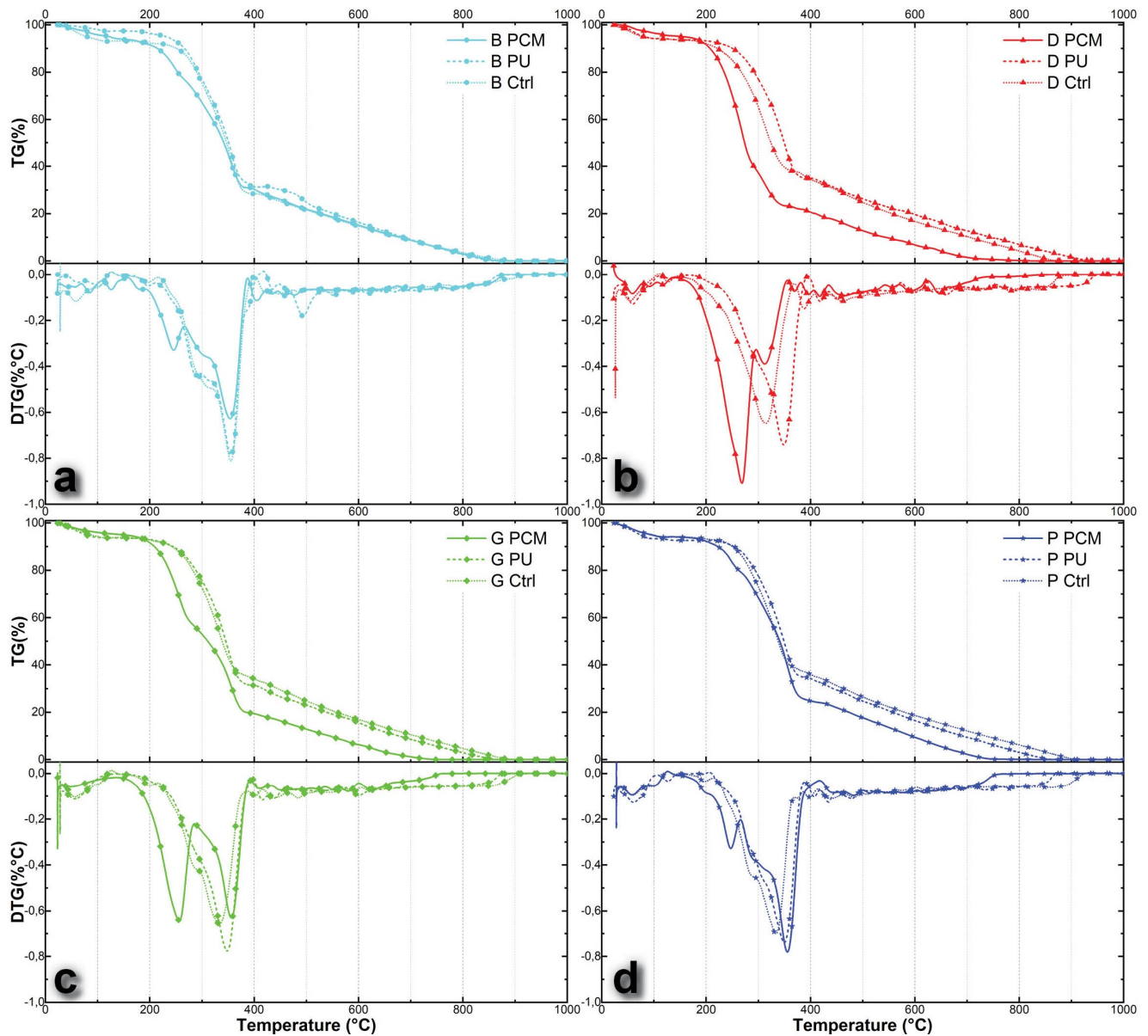


Figure 17: TG and DTG of *Bambusa tuldoidea* (a), *Dendrocalamus giganteus* (b), *Guadua augustifolia* (c) and *Phyllostachys aurea* (d) species samples under Control, PU, and PCM impregnated treatments.

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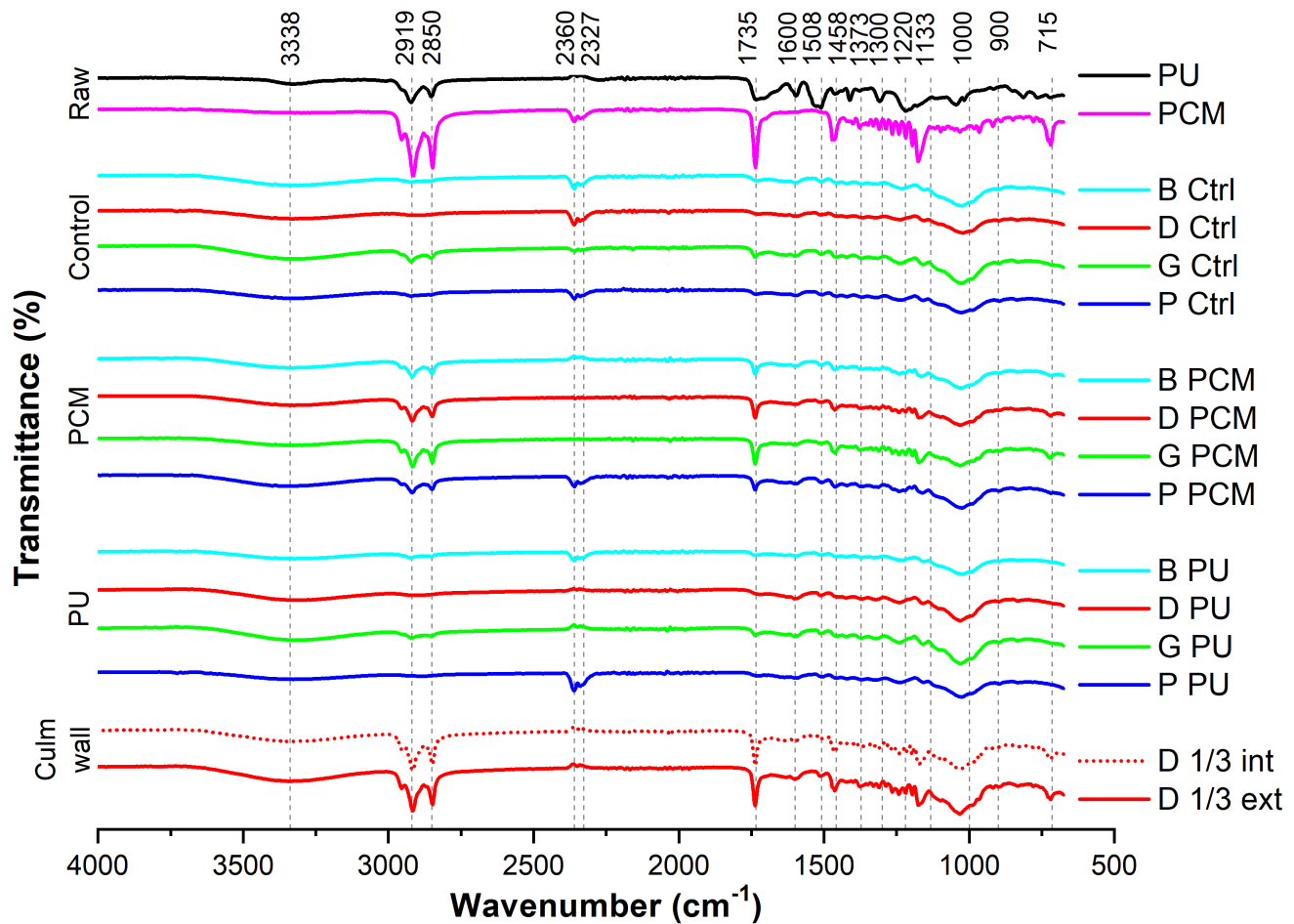


Figure 18: FTIR spectroscopy of Control, PU and PCM, samples of the four investigated species besides raw PCM and PU. Also inner and the outer third of bamboo walls samples.

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ARTICLE 3

Highlights

Bamboo-PCM: Comparative analysis of phase change material impregnated *Dendrocalamus giganteus* culm behavior exposed to thermal variation in wind tunnel essay

Fabício Rezende Fontenelle

- Wind tunnel test demonstrated that the influence of airflow significantly affects the rate of heat exchange.
- The conventional materials samples allowed better comparison of the absolute results obtained from the PCM-impregnated prototypes, helping to demonstrate their temperature anchoring and thermal energy storage capabilities.
- The coconut oil impregnated bamboo samples open up new possibilities for experimental campaigns to assess capabilities similar to industrially and commercially produced PCMs.
- The morphology of the samples with inherent irregularities due to the artisanal production, posed a potential problem and did not efficiently block the airflow into the insulated environment of the essay taking influence at the results obtained.

Bamboo-PCM: Comparative analysis of phase change material impregnated *Dendrocalamus giganteus* culm behavior exposed to thermal variation in wind tunnel essay

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ABSTRACT

In the pursuit of sustainability, where the construction industry exerts a substantial influence on environmental impacts, materials research represents a significant avenue in the quest for environmental efficiency in building design. This involves exploring materials sourced from renewable resources, like bamboo. In regions characterized by significant temperature fluctuations and intense solar radiation, the capacity of building enclosures to absorb heat assumes paramount importance. Consequently, materials with favorable thermal properties can enhance environmental comfort by minimizing the reliance on energy-intensive active cooling systems. This study aims to analyze the integration of naturally porous lignocellulosic bamboo biomass, capitalizing on its beneficial attributes, including its capacity for carbon sequestration from the atmosphere and its physical-mechanical strength, in combination with phase change materials (PCMs) and their thermal properties. To assess the most advantageous qualities, we employed culms of the *Dendrocalamus giganteus* species as a container for PCM and tested this thermal behavior in a wind tunnel. This approach was adopted to analyze the final product in terms of its thermal efficiency attributes, harnessing the substantial heat storage capacity provided by the PCM, in conjunction with the effect of the airflow in the energy exchange processes. Thermal variation tests revealed that the impregnated bamboo samples effectively mitigate temperature fluctuations by aligning them with the PCM's specific phase change temperature. Additionally, it was observed that air flow velocity has an impact on this phenomenon. A comparative analysis was conducted, focusing on two distinct types of bamboo samples: culms sealed with polyurethane resin (PU) and those impregnated with PCM, also sealed with PU. For the sake of comparison, samples of commonly used building materials, such as fiber cement, metal sheets, and ceramic roof tiles, were also tested as well as bamboo samples of the same species impregnated with coconut oil, in order to evaluate the thermal quality of this substance. The production processes aimed at achieving cost-effectiveness and minimal handling to enhance reproducibility. From an anatomical perspective, the pores within bamboo culms offered ample space for PCM storage, resulting in a substantial heat storage capacity. This study established that bamboo culms impregnated with PCM hold promise for temperature regulation in construction applications, with variations in airflow exerting an impact on the outcomes obtained.

1. Introduction

Bamboo stands as a sustainable natural resource with substantial potential to substantially reduce the environmental impact of the construction industry. This versatile plant species seems tailor-made for use in structural applications. Its ready availability, ease of distribution, swift maturation for harvesting, and favorable physical and mechanical characteristics makes it an ideal choice for construction purposes. It serves as an eco-friendly alternative to materials sourced from non-renewable resources or native forests that are exploited without proper management and conservation Palani, Goutham, Ayyappadasan and Praveena (2020).

On a parallel front, innovative research aimed at enhancing materials' thermal capacity and efficiency has made significant strides in exploring the capabilities of Phase Change Materials (PCMs). These materials possess the capacity to store latent energy, and when integrated into a building, they effectively stabilize temperature fluctuations, reducing the need for artificial climate control in response to

natural climate variations Zhang, Feng, Shi, Wang, Jin, Tian, Li, Wang, Zhao and Yan (2021). Within these materials, during a phase change caused by temperature variations that prevent the PCM from remaining in its prior state, there is a reorganization of intermolecular chemical bonds. This transformation necessitates the transfer of energy in both endothermic and exothermic directions, depending on the direction of the transition Sharma, Tyagi, Chen and Buddhi (2009). PCMs, at their melting or evaporation points, solidification or condensation, continue to absorb or release heat without altering their temperature for a certain duration, leading to a latent heat accumulation during this state transition, as illustrated in Figure 1 with a central "plateau."

As per Cabeza, Castell, Barreneche, de Gracia and Fernández (2011), latent heat storage offers a significant advantage in terms of its high storage density within small temperature ranges, rendering it suitable for both heating and cooling applications in buildings. It can be integrated as a passive system or as part of active climate control systems. Various research endeavors have been directed at identifying suitable structures for containing PCMs in their

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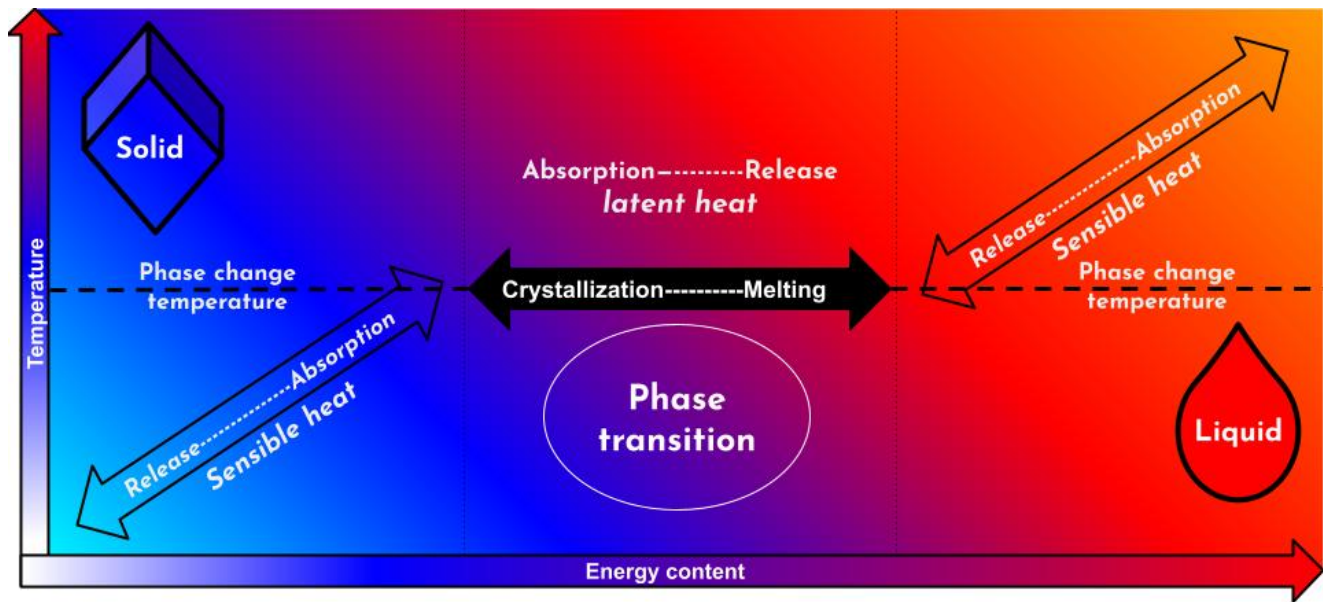


Figure 1: Energy content x temperature - the behavior of PCMs.

different physical states, which are crucial for optimizing their thermal efficiency.

PCMs encompass a range of chemical substances, with the most common ones falling into the organic category, predominantly paraffins and fatty acids. Additionally, inorganic substances like metals and hydrated salts are utilized, and there are also mixtures of organic and inorganic materials in various forms, referred to as eutectic PCMs Váz Sá, Almeida, Sousa and Delgado (2014). For this study, a bio-based organic PCM with a phase change temperature of approximately 24°C was chosen as well as it was decided to also evaluate the thermal behavior of extra virgin coconut oil, which has been studied for its thermal potential too Silalahi, Sukmawati, Sutjahja, Kurnia and Wonorahardjo (2017).

Porous materials have exhibited intriguing capabilities among the various materials used for PCM containment Huang, Chen, Li, Atinafu, Gao, Dong and Wang (2019). The current research seeks to leverage the inherent qualities of lignocellulosic materials, such as bamboo, which are naturally porous. This involves exploring the potential of impregnating PCM into the voids of bamboo's anatomical structure to enhance its thermal efficiency.

The bamboo species examined in this study, *Dendrocalamus giganteus*, is abundantly found in Brazilian territory and is frequently employed for rustic and artisanal purposes in traditional communities Rios and Farias (2021). Nevertheless, its industrial utilization or processing for commercially viable applications remains in its early stages. This research endeavors to unlock another potential advantage by harnessing the materials' inherent strengths in combination with PCM. Prior studies Fontenelle, Ferreira, Guimarães and Kuhn (2023) Fontenelle and Ferreira (2024) have shown promising attributes for this purpose .

The primary objective of this research is to assess the impact of wind flow speed on the thermal performance of the resulting objects, comparing it with other commonly used building materials. The aim is to preserve bamboo's inherent qualities while incorporating a sufficient quantity of PCM to bestow it with the desired thermal capacity for effective functionality.

2. Materials and methods

The primary material used in the various experimental stages was *Dendrocalamus giganteus* (D.) bamboo culms commonly known as "Bambu gigante" in Brazil. harvested at coordinates UTM Zone 23k: latitude: 7622850.81 mS and longitude: 545461.37 mE. Abundant clumping exotic species in the Southeast region of Brazil, used in civil construction and for producing slats for laminates, with large dimensions. In Figure 2a, we can observe the clump from which the specimens were extracted and the kind of section of stalks that were selected (fig.2b) and used for impregnation.

The phase change material (PCM) used was CrodaTherm 24 (fig.2c), a product with a chemical composition commercially protected and with a melting temperature of approximately 24°C and a solidification temperature of approximately 21°C. It was obtained through a donation from Croda International Plc Crodatherm (2020). This PCM has a specific temperature range for phase change that is very close to the ideal thermal comfort temperature for use in buildings The physical properties of this PCM are found in Table 1.

Additionally, a PU Vegetal – Type "V" sealing resin (fig. 2d) was used, which is a two-component polyurethane waterproofing agent of vegetable origin (derived from castor oil - *Ricinus Communis*), with an amber color Sinergia



Figure 2: Materials: *Dendrocalamus giganteus* clump where the research material was harvested (a), piece of bamboo culm as the used (b), commercial CrodaTherm 24 PCM (c), (d) resin used for sealing, PU vegetal – type "V" commercial. Commercial coconut oil (e) and used specimens of building materials (f) respectively from left to right: ceramic tiles, fiber cement, and metal sheet.

(2020). This resin has application and performance characteristics suitable for the sealing, durability, and waterproofing requirements of the research. Its natural origin from a renewable plant resource adds to its appeal.

Extra virgin culinary coconut oil, Cocoshow brand from COPRA, was also used (Fig. 2e), and it was purchased from a conventional supermarket with a solidification temperature of 25°C. The reported composition on the label is as follows in terms of fatty acids (g/100g): C6:0 Caproic: 0.48, C8:0 Caprylic: 6.61, C10:0 Capric: 5.22, C12:0 Lauric: 44.29, C14:0 Myristic: 17.68, C16:0 Palmitic: 8.40, C18:0 Stearic: 3.00, C18:1 Omega 9 oleic: 5.78 and C18:2 Omega 6 Linoleic: 0.93.

Three other commonly used materials in the construction industry for building envelopes were also tested: ceramic tiles, fiber cement, and metal sheet, as shown in Fig. 2f.

The research methodology essentially involved the following processes: collection and preparation of samples for analysis, essential physical and morphological characterization of the collected bamboo, thermal analysis with air flow to scrutinize the effect of impregnated PCM compared with other commonly used building materials, macroscopic and

microscopic visual examination of the samples, as well as chemical characterization.

2.1. Cutting and Preparation of Stalks and production of essay specimens

Three distinct treatments of the bamboo culm were considered: sealed with PU, impregnated with PCM and subsequently sealed with PU, and impregnated with coconut oil and also sealed with PU as summarized in Table 2. These treatments were selected to investigate not only the influence of PCM but also any potential effects, particularly concerning thermal behavior, associated with the impregnation of the coconut oil when exposed to variation in temperature and wind.

From the bamboo samples collected, those with the most appropriate suitable dimensions for the research objectives were selected. The sections chosen were extracted from the middle third of the bamboo stalk, with both the basal third and the upper third being excluded from consideration and then discarded. All procedures were carried out in accordance with the Brazilian bamboo standard NBR 16828-2 ABNT (2020). The selection criteria were primarily based on factors such as the relationship between diameter, node

Table 1

Physical properties of CrodaTherm 24 Guimarães (2023); Guimarães, Gomes, Oliveira de Araújo, Tadeu Lopes, da Gloria, Toledo Filho, Koenders, Caggiano, Mankel, Nazari Sam, Mendes de Andrade and Ferreira (2023).

Property	Typical Value	Unit
Thermal properties by differential scanning calorimetry (DSC)		
Peak melting temperature	24	°C
Latent heat (melting)	184	kJ/kg
Peak crystallisation temperature	22	°C
Latent heat (crystallisation)	−182	kJ/kg
Thermal properties by three-layer calorimetry (3LC)		
Peak melting temperature	23	°C
Total heat capacity (melting)	207	kJ/kg
Peak crystallisation temperature	23	°C
Total heat capacity (crystallisation)	213	kJ/kg
Other properties		
Bio-based content	100	%
Density at 20 °C (solid)	906	kg/m ³
Density at 40 °C (liquid)	843	kg/m ³
Flash point	226	°C
Specific heat capacity (solid)	3.7	kJ/kg °C
Specific heat capacity (liquid)	2.2	kJ/kg °C
Volume expansion 20–40 °C	7.5	%
Thermal conductivity (solid)	0.22	W/m °C
Thermal conductivity (liquid)	0.16	W/m °C
Thermal cycles without change in properties	10,000	cicles

Table 2

Treatment and denomination of the used samples in the thermal variation in wind tunnel essay.

Treatment	Objective	Denomination
Bamboo specimens (<i>Dendrocalamus giganteus</i>)		
Sealed with PU	control	PU
PCM impregnated and sealed with PU	analysis 1	PCM
Coconut oil impregnated and sealed with PU	analysis 2	Coc
Commonly used building materials		
Ceramic tiles	reference 1	Cer
Fiber cement tile	reference 2	Fb
Metal sheet	reference 3	Mt

spacing, and wall thickness. It is worth noting that the central portion of the bamboo culm is the most resistant to stress Oscar (2003). Additionally, this central region boasts a more uniform morphology characterized by regular node spacing and a cylindrical cross-section.

The collected bamboo stalks were subjected to a two-week period of natural drying or curing, ensuring that they were protected from exposure to adverse weather conditions. Following this, they were longitudinally cut to the appropriate dimension of 250mm as shown in figure 3a, enabling them to fit comfortably into the thermal test chamber for the hotbox essay and also underwent cross-sectioning to create curved strips (Fig. 3a, b and c).

The procedure followed a similar approach to the one employed in the production of slats (as illustrated in Figure 3d). To fulfill the Hotbox testing criteria, we aimed for minimal gap tightness to prevent excessive air flow. This involved the removal of septa or nodes found in the stalks, using tools like chisels and mallets. Additionally, each test specimen

was appropriately labeled for identification purposes. It's worth noting that each bamboo species possesses unique dimensions and characteristics based on their natural morphology. Consequently, we had to adapt both the procedure and the final slat shape of the samples to conform to these aspects and achieve the required overall width of 175mm, as depicted in Table 3.

These prepared specimens were then placed in an oven for induced drying (fig. 3d), following established procedures documented in literature. The Laboratory(2010) (US); Moreschi (2005); Moura, Dalla and Vieira (2018).

For PCM impregnation as the samples already had their final form for use in the thermal box test the test specimens were placed in plastic containers and immersed in PCM in liquid state (fig. 3f and g). Subsequently, these containers were placed in a laboratory desiccator connected to a vacuum pump (fig. 3h), which had previously been intercepted by a Kitasato setup to prevent contamination of the pump by liquid PCM. It's worth noting that due to the ambient

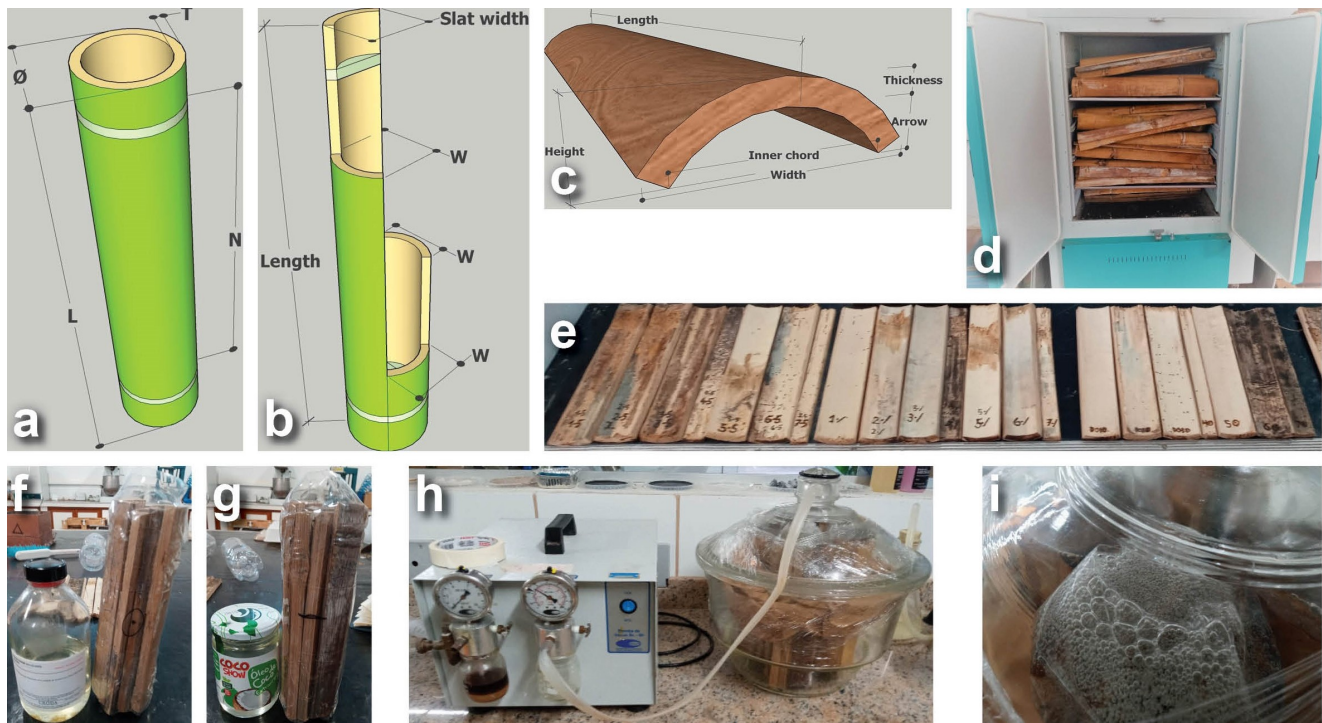


Figure 3: The original shape of the sample from the impregnation process is depicted in (a), and (b) illustrates the schematic of the longitudinal cut of the stalks followed by the expected final slat shape of the slat (c). The manufactured specimens (e), the drying oven process (d), sample conditioning for impregnation (f and g), vacuum pump treatment (h), prominent bubbles on the top of samples in the impregnation process (i).

temperature being above 24°C, there was no need to heat the PCM.

The negative pressure pumping was carried out until confirming the vacuum in the desiccator, as indicated by the pressure shown on the pump's manometer. In this vacuum condition, it is possible to observe the appearance of bubbles on the cross-sectional surfaces of the bamboo culm samples (fig. 3i, which represent the release of air from the porosity within the object's anatomy. This process was repeated until the appearance of bubbles ceased, which occurred after approximately 24 hours. After completing the impregnation, the samples were drained, and excess PCM was removed using absorbent paper towels. Subsequently, they were stored in a refrigerated environment (at approximately -6°C) to prevent PCM loss due to leakage resulting from its liquefaction.

The sealing process was accomplished by mixing the PU resin components, but with a solvent dilution to enable the use of a compressed air spray gun. There was also a need to carry out the process quickly due to the rapid drying of the PU resin. The test specimens were placed on a suitable support for easier application (fig. 3e). As the ambient temperature was below 24°C on the day of the procedure, it was possible to carry it out in an open space.

2.2. Basic characterization

In order to establish correlations between observed phenomena and the unique properties of each material, various general aspects were assessed throughout the process,

including morphological and anatomical characteristics, as shown in Table 3.

The samples were exposed to natural air drying to reach hygroscopic equilibrium Forest Products Laboratory (US); Moura et al. (2018); Zen, Monteiro, Schaeffer, Kaminiski and Klitzke (2019), and the determination of apparent density was the ratio between the dry mass (weighed using a precision scale following oven drying) and the water-saturated volume (determined using the displaced liquid method based on Archimedes' principle), while considering the irregular shape of the samples Forest Products Laboratory (US); Moersch (2005). The mass measurements were also taken before and after impregnation, thus enabling the determination of the content of these substances in the final sample.

2.3. Thermal variation in wind tunnel essay

This test was conducted using a pre-existing wind tunnel equipment placed at the Animal Environment Laboratory of the Department of Agricultural Engineering - Federal University of Lavras, which is typically used for analyses in this specific field. The wind tunnel's main feature is the ability to introduce airflow at various speeds into the set of parameters being evaluated. In addition, another specific piece of equipment designed for analyzing thermal variations in static air, referred to as passive chamber, was used Fontenelle and Ferreira (2024); Fontenelle et al. (2023). The experimental treatments consisted of evaluating different effects of staggered wind speeds on the heat exchange

Table 3

Morphological characteristics of the original bamboo samples.

Culms			Average characteristics of the nodes	
Average general dimensions (mm)			Amount	Average distance (mm)
Diameter [Ø]	Length [l]	Wall thickness [t]		
140	250	8	0	450

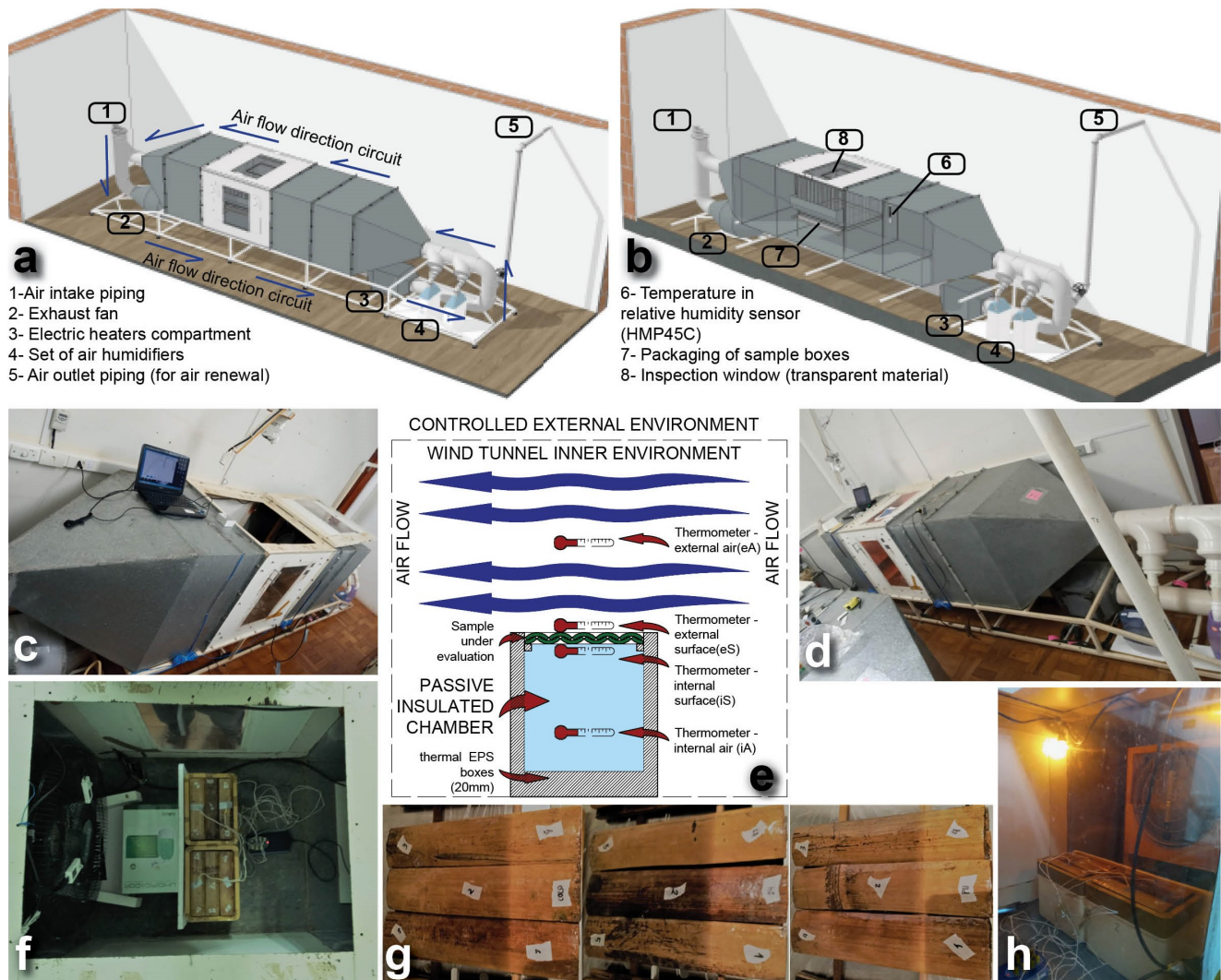


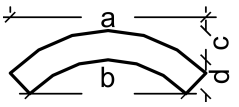
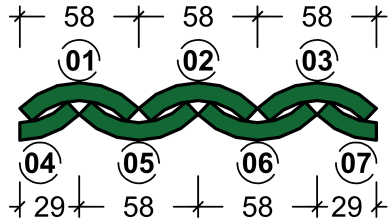
Figure 4: Schematic perspective (a) and section (b) of the wind tunnel equipment with the main accessories Bahuti et al. (2023). Experimental apparatus (c, d) equipped with thermal insulating boxes (f), extra fans and monitoring thermometers (h). (e) Schematic diagram of the setup environment with the location of the temperature sensors. Three groups of samples from the different bamboo treatments (g).

processes occurring on the samples with a constant upward and downward temperature variation. In summary, the wind tunnel is a large circular circuit with inducing fans to create airflow, heating elements to control temperature, and equipment for regulating the relative humidity of the air within the system as shown in figure 4.

The wind tunnel (Fig. 4a-d) was equipped with a set of electrical resistances (totaling 2400 W), air humidifiers (total flow of 600 mL of water), an exhaust fan (40 cm in diameter

and flow of 4200 m/h) and a lighting system. In addition, inside the tunnels, a set of thermally insulated boxes was installed performing the function of passive chambers (fig. 4 e, f, h). This setup was modeled based on an instrument designed for measuring thermal insulation capacity, commonly referred to as a "hotbox" Terra (2018); Eugênio (2016). It involved the use of two 8-liter thermal insulation boxes placed side-by-side made of polystyrene (EPS) with an approximately 20 mm thickness. These boxes were stacked

Table 4
Morphology, organization, and dimensions of the samples as placed at the passive chamber.

Species	Cross-sectional diagram and sample organization	
	Average dimensions (mm)	
<i>Dendrocalamus giganteus</i>		a=58; b=50; c=8; d=7

with an EPS support, which introduced a septum between them and the external environment, serving as the placement area for the samples to be evaluated, effectively acting as a diaphragm which, due to its position, is also subject to wind action on its outer surface. The objective of the test was to assess the attenuation of thermal load between the two environments (wind tunnel air and passive chamber internal air) with initially equal temperatures.

In order to accelerate the temperature rise the tunnel was also equipped with a heat-emitting element, in this case, an incandescent bulb (glass bulb with a Tungsten filament and E27 non-ferrous socket, with a power of 15 W and a voltage of 127V). The insulated boxes (passive chambers) received the heat variation from the “external air”, which was attenuated by the samples (fig. 4e), creating an obstacle between the two environments, as outlined in the scheme presented in Table 4.

To ensure accurate temperature measurements, eight type K thermocouples were employed in a data collection system, on the external (eS) and internal surfaces (iS) of the samples, with temperature measurement and recording capabilities, boasting an accuracy of four decimal places in °C. Temperature readings were periodically recorded at predefined time intervals using software provided by the manufacturer of the commercial equipment, the Pico Technology USB TC-08 thermocouple data logger with PicoLog data logging software. We also used, both in the tunnel environment, referred as external air (eA) and in the internal environment of the passive chamber, internal air (iA), six HOBO (type onset 1-800-Loggers) temperature and relative humidity sensors, in addition to the sensor present in the tunnel type HMP45C (Vaisala®) with accuracies of 0.3°C.

To conduct the experiment, it was important to note that the PCM used had a melting temperature of approximately 24°C, and the heat storage process and the phenomenon under investigation occurred within this temperature range. Consequently, the experiment was planned to allow the temperature to traverse this range with a substantial safety margin both above and below this value. This was necessary to observe the phenomenon in both its heating and cooling phases. The experimental procedure commenced

with the organization of the thermometers and parameters in the application to ensure accurate data recording (data collection frequency, designations, etc.). Subsequently, the wind tunnel heating system and the incandescent lamp is activated, initiating the temperature increase in the system, referred to as “**Phase 1**”. The room where the experiment was conducted was climate-controlled at a temperature of approximately 19°C, significantly below the PCM’s melting point. Therefore, the wind tunnel setup needed to elevate the temperature above 24°C but not significantly beyond 30°C to avoid a substantial deviation from the ambient climate. This choice determined the power of the heating element. In order to accelerate the test stage in which the behavior of the sample is measured when the temperature decreases (**Phase 2** or cooling), an extra agent was added for this purpose using containers (with controlled volume) containing ice.

The Phase 1 (heating) of the experiment, focused on temperature increase, started with the setup activation when the system was all around 19°C. The temperature in the wind tunnel was raised to values exceeding 35°C, and then the temperature increment gradually decreased, as observed by the thermometers in both environments. This indicated the stabilization of the system with the energy source activated, a process that took 120 minutes. In the Phase 2 (cooling), involving temperature decrease, the wind tunnel, which contributed heat, was turned off the air intake piping, air outlet piping and the inspection window was opened as well the ice containers are placed inside the wind tunnel environment. This allows a rapid temperature reduction to the setup temperature. Gradually, the influence of the barrier/sample on this cooling process was also noted. This temperature reduction and stabilization process also took 120 minutes.

The thermometers in the system were positioned at four levels (fig. 4e), with duplicates, to guarantee the reliability of the collected data. The frequency of temperature recording was every 1 minute and they were arranged as:

- **External Air (eA)** Temperature sensors: positioned at the geometric center of the wind tunnel volume.

- **External Surface** of the sample (**eS**) temperature sensors: placed on the surface exposed to the environment of the wind tunnel of the evaluated barrier.
- **Internal Surface** of the sample (**iS**) temperature sensors: placed on the surface exposed to the environment of the passive chamber of the evaluated barrier.
- **Internal Air** (**iA**) temperature sensors: positioned at the geometric center of the volume of the passive chambers.

Throughout the experimental period, the setup was kept in relative humidity of 60 %, automatically controlled by the monitoring system of a datalogger (CR1000, Campbell Scientific®), a relay controller (SDM-CD16AC, Campbell Scientific®) and a channel multiplexer (AM16/32B, Campbell Scientific®). The air velocity inside the wind tunnel was set at three different rates, minimum wind speed - 0.2 m/s (min), median - 1,7 m/s (med) and maximum - 3,2 m/s (max). Such speeds were achieved by adjusting the fan power and systematically measuring its speed at eight geometrically distributed points on the sample's surface using a Type K/J hot wire anemometer (Impac brand, YK-2005AH model).

2.4. Complementary characterization - microscopy and ultrastructural analysis

In order to proceed an anatomical examination of the plant structures, allowing observation of tissue patterns, vascular structures, and porosity, light optical microscopy was used as well as the following instruments: Stereomicroscope with epifluorescence SMZ 1500 (Nikon), Confocal Microscope LSM 780 (Carl Zeiss) and Ultra-high-resolution Field Emission Scanning Electron Microscope - STEM - CLARA model (TESCAN, 2021). To observe internodal regions, and cross-sectional cuts to capture images of the stalks Krause (2015) ; Júnior (2012). These samples, measuring approximately 10 mm x 5 mm x 5 mm, were derived from bamboo strips and placed in molds for embedding. Subsequently, the blocks underwent vacuum impregnation with embedding epoxy resin (Epofix) from the Struers brand. The blocks were sanded using a sequence of progressively finer grits on an orbital sander and subsequently polished with diamond paste on an orbital polisher. This procedure was carried out at the Centro de Tecnologia Mineral (CETEM-UFRJ) Krause (2015); Krause, de Andrade Silva, Ghavami, Gomes and Filho (2016).

2.5. Chemical characterization

For thermal analysis through thermogravimetry (TGA), which aimed to confirm the chemical composition of the samples, a TGA Q500 TA Instruments thermal analyzer (Delaware, USA) was used, set with a heating rate of 10°C/min. Between 7 and 10 mg of powdered sample were placed in the crucible and heated from 25 to 1000°C. The analysis conditions included a synthetic air atmosphere (80% N₂ and 20% O₂) flowing at a rate of 60 mL/min (Raabe

et al., 2015). Critical temperatures for mass loss, including the initial temperature, the temperature range within which losses between 70% and 80% of the sample mass occurred (shoulder temperature), and the temperature at which the final mass stabilized (final temperature), were determined through examination of the TG and derivative TG curves.

Fourier-transform infrared spectroscopy (FTIR), vibrational infrared spectroscopy analyses were performed using a Varian 600-IR Fourier-transform infrared (FTIR) spectrometer equipped with a Pike Technologies GladiATR accessory for attenuated total reflectance (ATR) measurements at a 45° angle, utilizing a zinc selenide crystal. The spectral range analyzed was from 400 to 4,000 cm⁻¹, with a resolution of 2 cm⁻¹ and 32 scans. For chemical analyses, the samples were processed into a homogeneous form consisting of powder or fine grains of the samples. This approach ensured consistency in the analytical procedures.

3. Results and discussion

3.1. Basic characterization

The impregnation index achieved in the samples was always above 14%. This index is expressively higher than what was achieved with the impregnation method using the solid culm without immersion in other bamboo species such as *Phyllostachys aurea* (7.11%) Fontenelle et al. (2023). Impregnation reached an average of 15,16% with the PCM and 14,39% with the coconut oil with an original apparent basic density of 0,41 g/cm³ average.

3.2. Thermal variation in wind tunnel essay

The results of the carried-out experiment are depicted in Figures 5, 6, 7, 8, 9, 10 and 11, illustrating temperature profiles recorded by the thermometers positioned within the setup, as previously detailed as well as the subtraction between the antagonistic positions of the present thermometers. The samples underwent thermal testing encompassing both heating and cooling cycles (**Phases 1 and 2**).

The results were presented individually for each specimen in the proposed treatments (Fig. 5, 6 and 7) and combined for better data comparison visualization (Fig. 8). The solid, dashed and dotted lines represent respectively the maximum (3,2 m/s), median (1,7 m/s) and minimum (0.2 m/s) air flow speed. Each color represents the average measurement of a pair of thermometers positioned simultaneously in the regions as described, with **eA**, **eS**, **iS** and **iA** respectively in black, red/orange, gray/light gray and blue/cyan colors taking into account the different types of samples, it is also possible to distinguish each specimen by its specific symbol as shown in the lines.

The results presented in Figure 5 shows that the temperature variation profile in the thermometers of the PCM samples and those resin-coated with PU are quite distinct despite similarly, in both samples, at the temperatures of the external air and the external surface of the samples rising rapidly due to the fast heat increase at the wind tunnel environment (fig. 5a-c). However, there is a significant delay

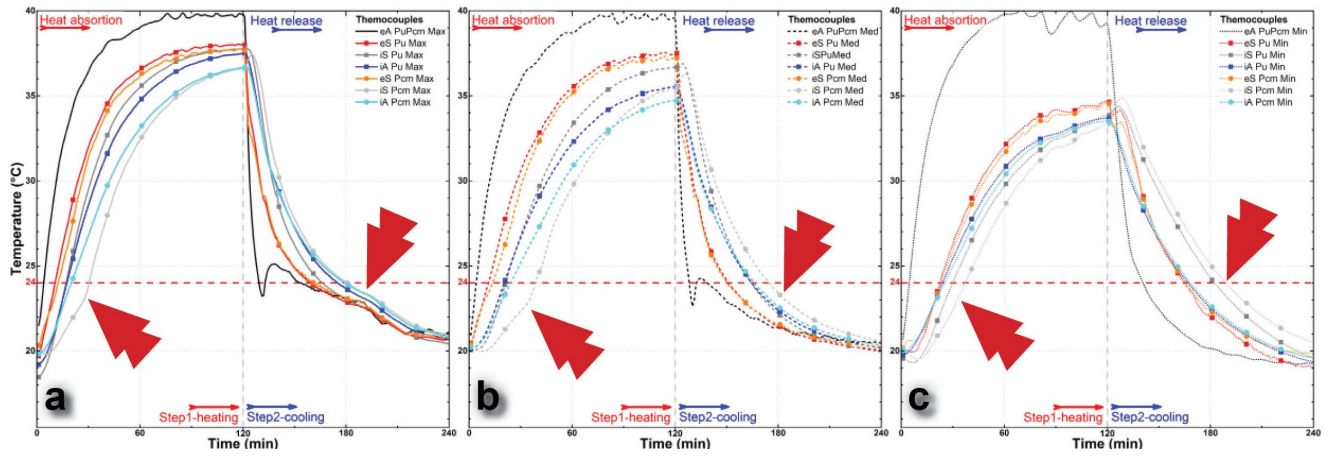


Figure 5: Temperature profiles for the thermometers at the wind tunnel experiment for coated bamboo with polyurethane resin (PU) and PCM impregnated bamboo (PCM) at maximum (a), median (b) and minimum (c) air flow speed. The arrows highlight points of special interest

in heating the sample's internal surface and an even more prominent delay in the interior air of the passive chamber in the same samples. This delay is, however, much more pronounced when we look at the curve of the sample treated with PCM, highlighting that even the external surface of the PCM-treated sample experiences a slight delay in temperature increase.

A comparison between the PU and PCM samples shows that the temperature of the resin-coated was slightly higher in all thermometers, however, there is no visual evidence of a change in the temperature growth trend, as the curves exhibit a constant linear trend, with parallelism between the external air (eA) and all the other thermometers, however notably, when the PCM-impregnated sample reaches approximately 21–24°C, the curve trends begin to shift. This shift coincides with the PCM undergoing a phase change, absorbing heat, and consequently delaying the temperature increase. For instance, while the internal surface thermometers of the non-impregnated samples (iS PU) takes approximately between 15–20 minutes to reach 25°C (crossing the melting point of the PCM), the PCM-impregnated sample (iS PCM) requires approximately up to 40 minutes, indicating a relevant longer time to reach the same temperature. This result demonstrates the efficacy of PCM-impregnated bamboo culms for thermal energy storage where there is visibly an action by the PCM in anchoring the temperature change of physical state around 24°C.

Another clearly visible aspect in these three illustrated graphs (Fig. 6a–c) is the difference in the speed at which all thermometers, with the exception of the external air (eA) in the wind tunnel environment, exhibit a slowing down of their heating as the wind speed decreases, demonstrating a significant influence of the air flow velocity on the heat exchange occurring in the system. While the external environment, for example, exceeds 35 degrees in all three speeds tested in about 10 minutes of the experiment (eA PuPcmMax, Med, or Min, Fig. 6a–c), with a maximum airflow speed of 3.2 m/s, the resin-coated samples (eS PuMax, Fig. 6a) reach this

threshold only after approximately 40 minutes at medium speed (1.7 m/s) and after about 55 minutes at the minimum speed of 0.2 m/s, they do not even reach this 35°C level.

There is also an unexpected observable effect in the three presented graphs (Fig. 5). The temperatures of the internal surfaces (iS PcmMax, Med, and Min) of the PCM-containing samples exhibit a greater delay in their heating and cooling processes than the internal air (iA PcmMax, Med, and Min) of the supposedly insulated passive chamber. This effect is likely related to the gaps present in the composition of the sample units in the partition made. In other words, despite the delay caused by the PCM's temperature anchoring and heat accumulation effects, due to the existence of spaces for airflow and the added wind speed, this partition of the samples does not prove to be effective or sufficient for retaining the passage of this energy.

When it comes to the secondary samples in this research, which serve the purpose of comparison with conventional building materials as well as coconut oil-impregnated bamboo in comparison with the PCM's performance, we can observe in Figure 6 and 7, with regard to the latter (Fig. 6), that the thermal behavior revealed in the displayed curves is highly similar to the behavior observed with PCM impregnation. There is a significant delay in temperature gain, with the internal air of the passive chamber (iA Coc) reaching higher temperatures than the internal surface (iS) of the samples, once again revealing the possible influence of gaps. However, there is no significant distortion in the curve's trend, as observed in the case of the commercial PCM. In other words, there is no clear anchoring to a specific temperature range; instead, there is a spreading of this effect.

The effect of wind speed (Fig. 6 and 7) on the rate of heat exchange is also noticeable in all samples, as observed in Figure 5, further emphasizing this influence. As for the behavior of the three conventional materials analyzed—fiber cement tiles, metal plates, and ceramic tiles—the results show similar behavior among them. There is a parallel trend between the variation in external air temperature (eA) and

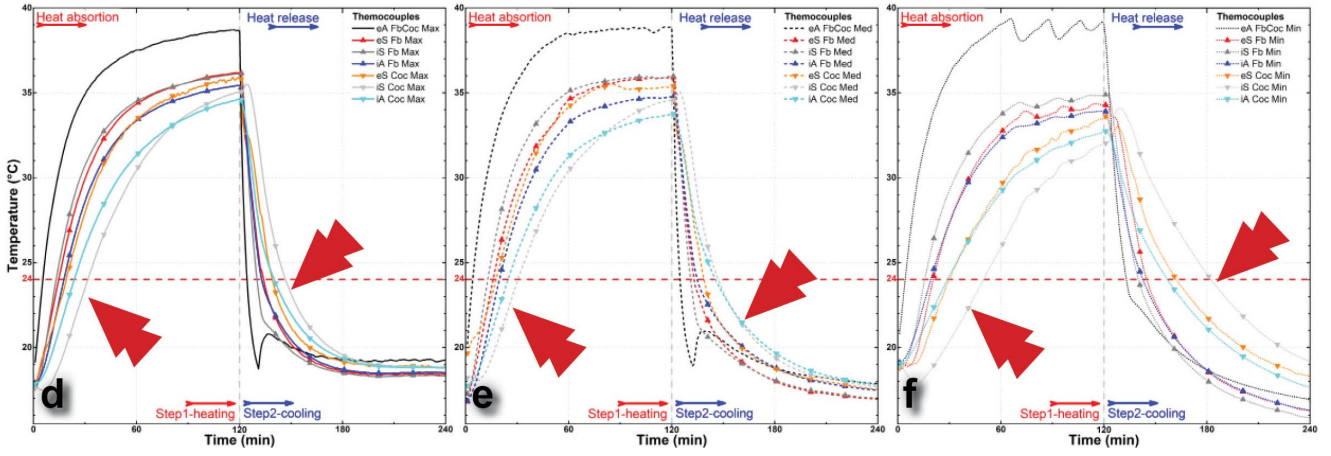


Figure 6: Temperature profiles for the thermometers at the wind tunnel experiment for coconut oil impregnated bamboo (Coc) and fiber cement tile (Fb) at maximum (d), median (e) and minimum (f) air flow speed. The arrows highlight points of special interest

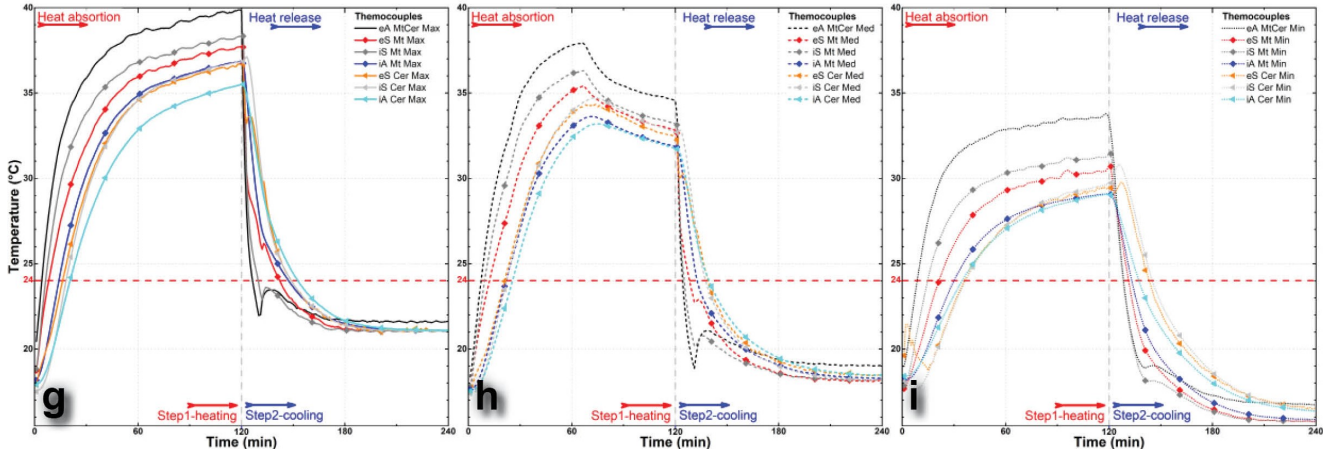


Figure 7: Temperature profiles for the thermometers at the wind tunnel experiment for ceramic roof tile (Cer) and metal plate (Mt) at maximum (g), median (h) and minimum (i) air flow speed.

all other variations, both in the external surfaces (eS) and internal surfaces (iS) of the samples, as well as in the internal air (iA) of the passive chamber. In these cases, the internal air consistently showed a delayed calorie gain and loss compared to the overall system, unlike what was observed in the bamboo samples.

The data presented in Figure 8, which compiles the temperature profiles isolated by sample at the three wind speeds, have been reproduced here because they make the individual effect of air flow velocity on temperature gains at various points in the setup even clearer. It's worth emphasizing in the graphs in Figure 8b and c, with the PCM and coconut oil-impregnated samples, respectively, how much the dotted lines representing the lowest wind speed are separated from the dashed lines representing the median speed, and from the solid line with the maximum speed.

Another observable fact is the presence of more prominent roughness in the curves that represent the minimum

speed, highlighting irregularities in the heat exchange process. This is quite different from what occurs at higher air velocities.

The results that can be observed in Figures 9 and 10 also demonstrates analyses conducted regarding the temperature difference ($\Delta T^{\circ}\text{C}$) between the profiles measured for the external air as opposed to the internal air (iA-eA), additionally, the differences between the external surface and the internal surface (iS-eS) highlight the delay in conduction and the storage of thermal energy through the samples.

Observing the results, it's possible to notice a greater difference occurring between the internal air and the external air in almost all cases, as well as a tendency for the difference to stabilize when the variation of the temperature at the wind tunnel environment also stabilizes, always around the 90 min. A larger difference is also evident in the PCM, coconut oil and PU samples respectively in that order, both in terms of the difference between the internal and external surfaces and between the internal and external air (fig. 10a-c).

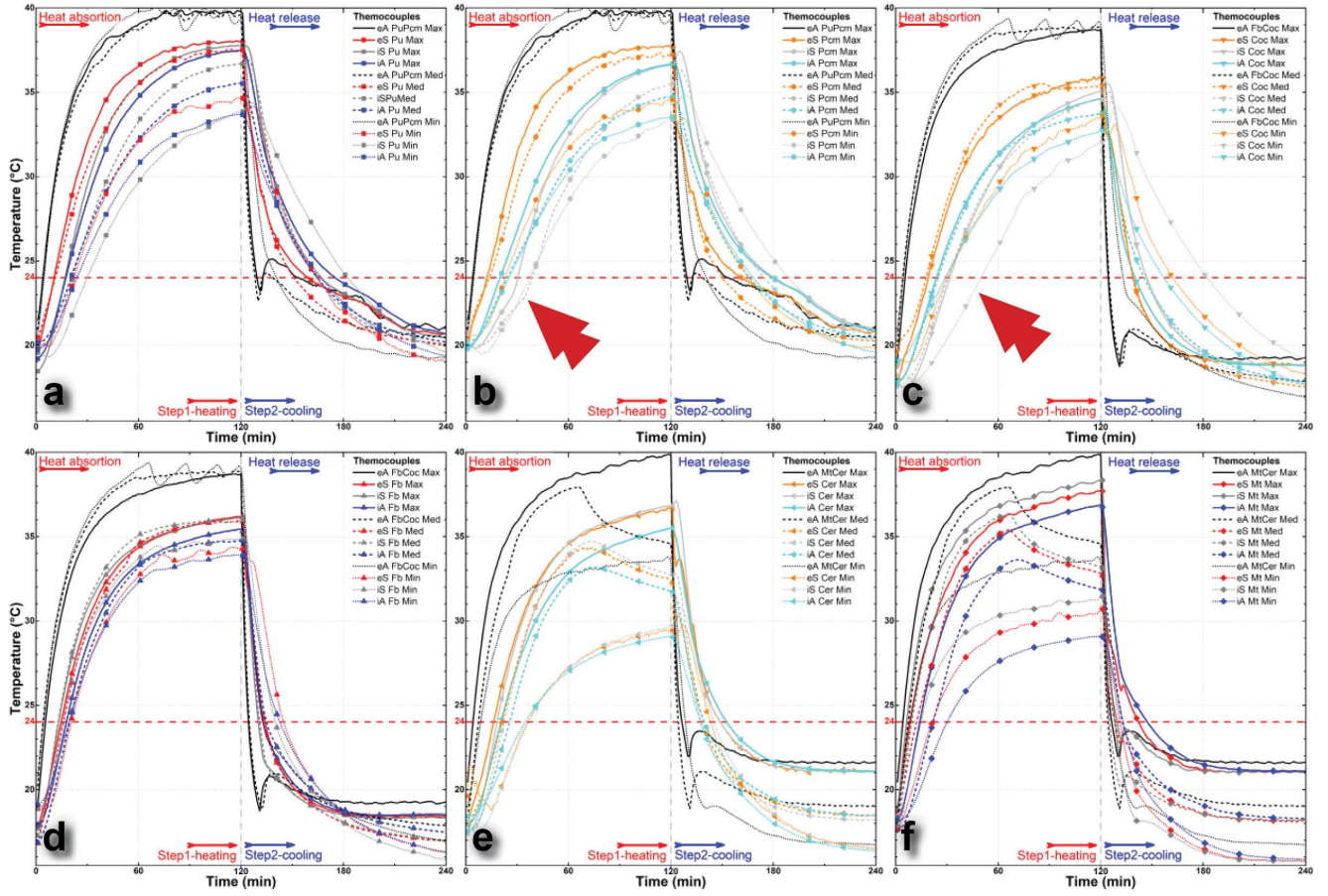


Figure 8: Temperature profiles for the thermometers at the wind tunnel experiment for the three different wind speeds (max, med, min) in each isolated sample: (a) PU coated bamboo, (b) PCM impregnated bamboo, (c) coconut oil impregnated bamboo, (d) fiber cement tile, (e) ceramic roof tile and (f) metal plate. The arrows highlight points of special interest

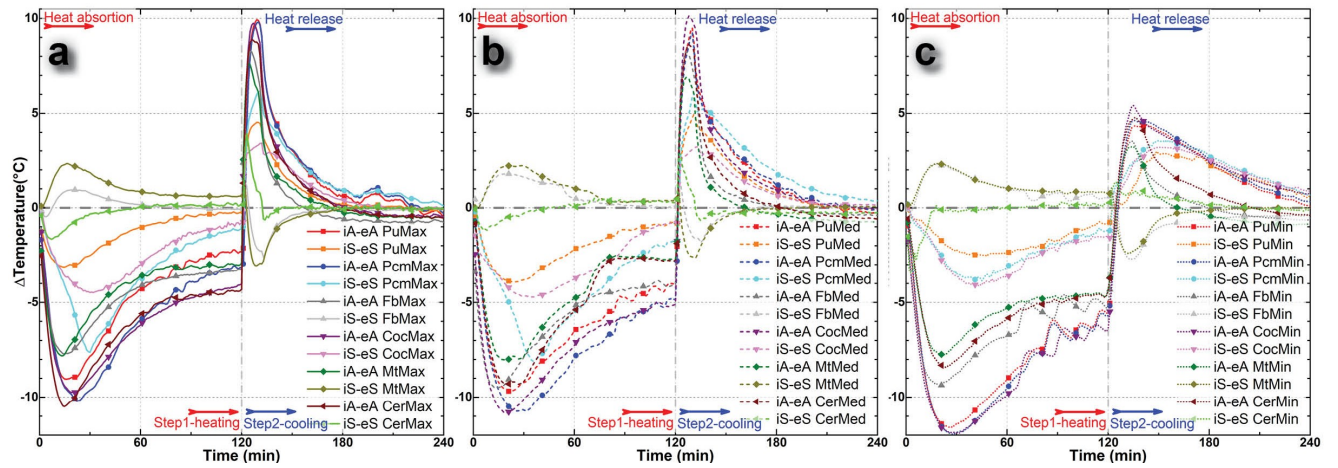


Figure 9: Temperature profiles for differences between the external air minus the internal air (iA-eA), and the external surface minus the internal surface (iS-eS) of all the samples at maximum (a), median (b) and minimum (c) air flow speed.

Regarding the samples treated with PCM (fig. 10b), there is also a clear distortion in the graph profile with its maximum point occurring around the 30th minute of the experiment, where a peak can be observed. This peak is also noticeable during the second phase of the experiment, where the external air temperature becomes lower than the

internal air temperature after the 180th minute. These peaks are likely caused by the action of the PCM, which anchors the temperature due to the storage of thermal energy, either absorbing or releasing heat. This effect is also not observed in the samples with coconut oil (fig. 10c)

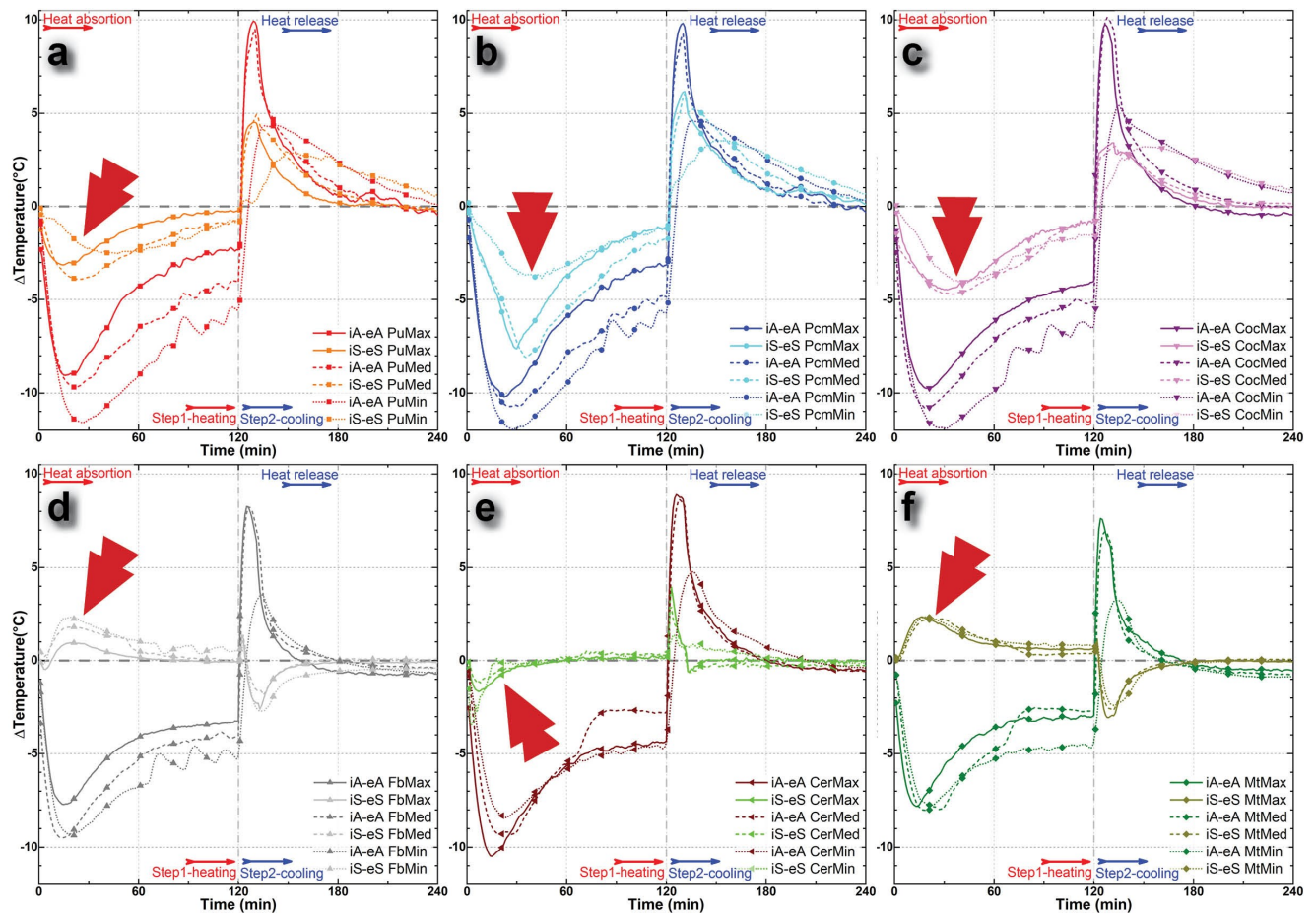


Figure 10: Temperature profiles for differences between the external air minus the internal air (iA-eA), and the external surface minus the internal surface (iS-eS) in each isolated sample: (a) PU coated bamboo, (b) PCM impregnated bamboo, (c) coconut oil impregnated bamboo, (d) fiber cement tile, (e) ceramic roof tile and (f) metal plate.

When observing the samples of conventional building materials (Fig. 10d-f), it is possible to notice a reversed effect in the temperature gain expressed on the surfaces of the samples (iS-eS) in both the metal plate and fiber cement samples (Fig. 10d and f). The properties of high thermal conductivity of these materials are widely known, and this effect is not observed in the ceramic tile (Fig. 10e), which is also known for being a more effective thermal insulator. Nevertheless, when comparing ceramic with all bamboo samples, whether impregnated or not, substantial differences are observed.

3.3. Microscopy and Ultrastructural Analysis

Under 10x magnification, as illustrated in Figure 11, one can clearly discern the anatomical structures comprising bamboo, along with the significant presence of voids at various scales. Notably, larger voids can be seen within the sap-conducting vessels of the parenchyma, a structure primarily composed of lignin, which forms the cellular framework. In Figure 11a, these voids are filled with solid-state PCM, giving them a waxy appearance, a feature absent in Figures 11b and c, where the untreated bamboo stalk maintains its natural state, causing the sap-conducting vessels to appear

as distinct dark polygonal shapes. At 125x magnification in Figure 11c, it becomes possible to observe a more detailed perspective, including a bundle of sap-conducting vessels with more prominent voids, as well as the intercellular and intracellular spaces within the raw bamboo culm.

Figure 11d-g also presents a sequence of timed images, captured at 20 second intervals, on a 10x scale. These images document the melting and subsequent release of PCM impregnated within bamboo when subjected to temperatures exceeding 24°C, its melting point. It is important to note that this leakage is exclusively observable in the cross-sectional cut section of bamboo, emphasizing the potential loss in the absence of PU resin sealing in this area.

In figure 11h images obtained by MEV it is possible to observe, on a comparative scale, the large voids present in the anatomical microstructure of bamboo plant tissues and in Figure 11i-k, we observe the scanning of the cross-sectional surface of the bamboo culms performed using the confocal microscope, with an assessment of its roughness. Both the three-dimensional image and the surface profile of the section demonstrate how rough it is.

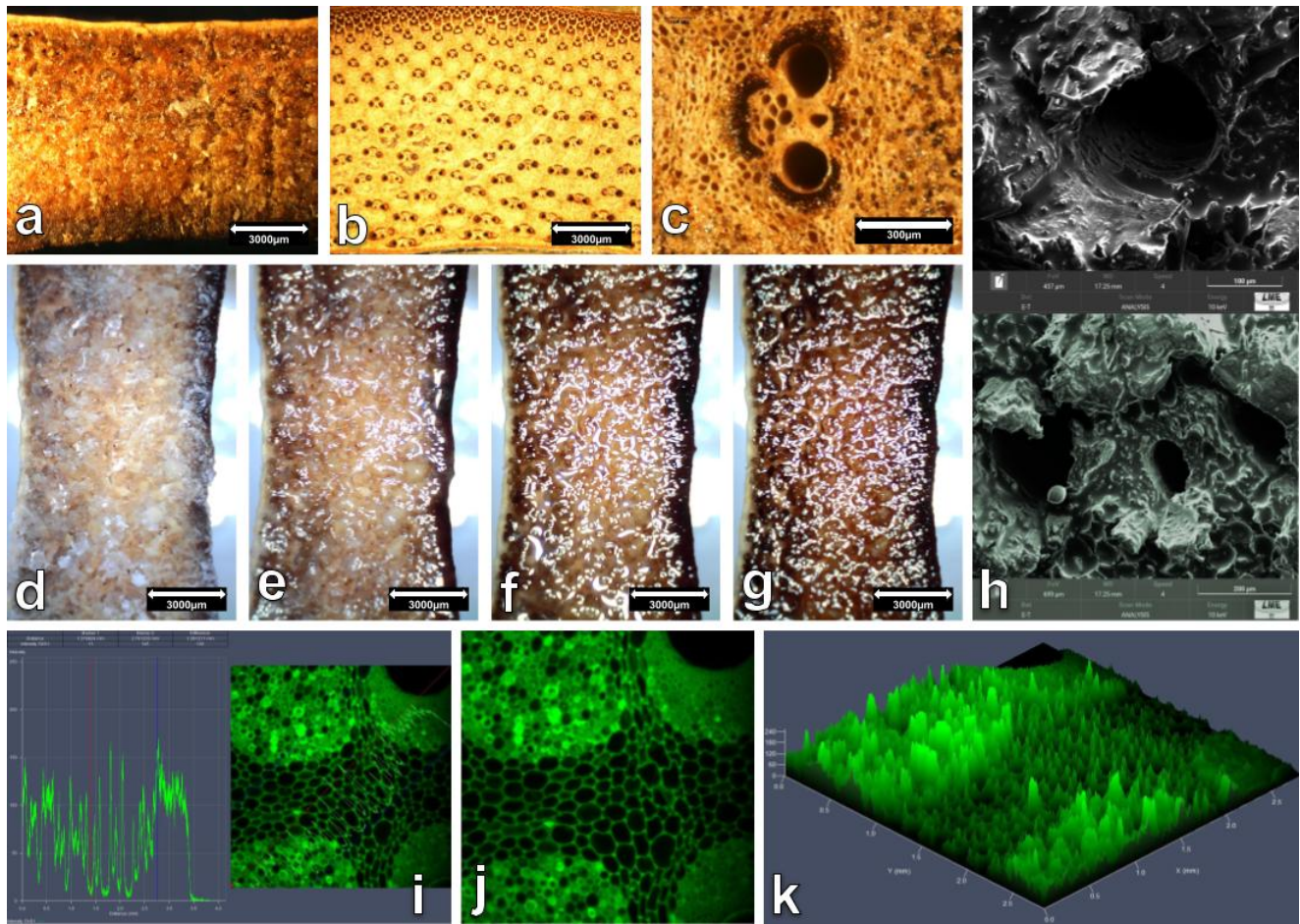


Figure 11: Images obtained by Stereomicroscope (at 10x magnification (a-b) and 125x magnification (c)) of the internodal cross-sections of *Dendrocalamus giganteus* bamboo culms with PCM impregnation (a) and without impregnation (b-c). (d-g) Successive images at 10x magnification extracted from the melting process of PCM impregnated of bamboo culms, taken every 20 seconds. (h) Images obtained by Ultra-high-resolution field emission scanning electron microscope (MEV) of the internodal cross-sections and obtained by Confocal Microscope (i-k).

3.4. Chemical characterization

Figure 12 showcases thermogravimetry (TG) and derivative thermogravimetry (DTG) curves, shedding light on the chemical composition of samples extracted from materials used in a wind tunnel experiment. These samples encompass raw bamboo and polyurethane resin (PU). Typically, the initial mass loss observed up to 100°C is attributed to the release of free water, except in PU (refer to fig. 12a), during the initial phases Guimarães (2023); Guimarães et al. (2023). Further noteworthy mass loss events can be discerned in these curves, as follows:

1. In the raw bamboo sample referred as “D Ctrl”, (*Dendrocalamus giganteus* (fig. 12a), there is an initial peak, occurring approximately between 250 and 320°C, corresponding to the degradation of hemicellulose (typically in the range of 150 to 350°C Kim, Kim, Kim and Yang (2006)). Subsequently, a sharp peak centered at 348°C signifies the degradation of cellulose. Finally, a lower-intensity peak, slightly above 400°C, likely corresponds to the degradation of lignin, typically occurring within the range of 250 to

600°C. These constituents are present in substantial proportions in the vegetative tissues of the examined bamboo species, as evident in all the analyses presented.

2. In the PCM-treated sample curve (fig. 12a), a peak emerges shortly after 200°C, distinguishing it from samples treated without PCM. This disparity arises from the degradation of PCM, an organic ester, commencing at relatively low temperatures Poletto, Ornaghi and Zattera (2014), with a center around 234°C. These samples also exhibit peaks similar to those observed in natural samples of these plant tissues.

3. In the sample treated only with PU resin (fig. 12a), it's important to note that, according to literature sources Azevedo, Santana, Nascimento, Claro Neto and Lepienski (2009); Müller, Rubio-Pérez, Bach, Muñoz-Rujas, Aguilar and Worlitschek (2020), polyurethane experiences mass loss in two decomposition stages. The first stage begins at 240°C and ends at 350°C, associated with the rupture of urethane bonds. The second stage initiates at 500°C and pertains to the decomposition of ester bonds within the polyol. These peaks are distinguishable, even if there's potential overlap

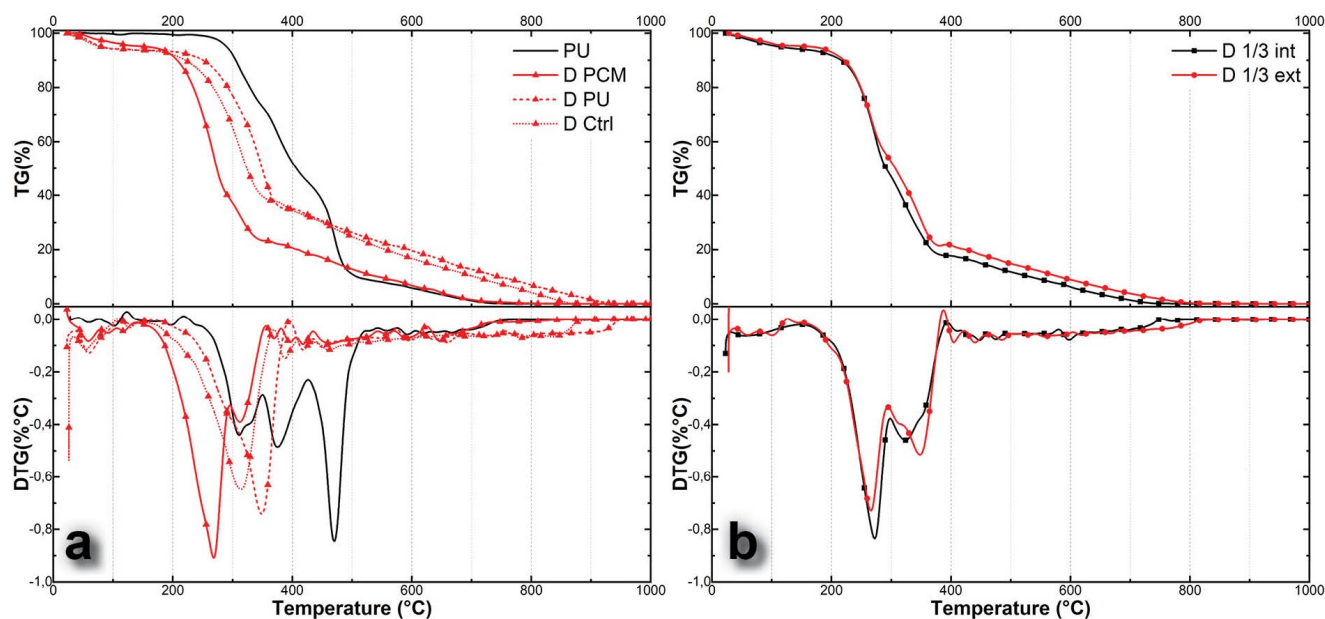


Figure 12: (a) Thermogravimetric analysis curves, TG and DTG for, raw PU resin, PU coated bamboo (D.PU), PCM impregnated (D.PCM), and raw bamboo samples of the investigated specimens, and (b) inner (internal) and the outer (external) third of bamboo walls.

with hemicellulose degradation occurring at similar temperatures, especially when compared to the raw PU profile presented.

4. The samples depicted in fig.12b were included in the analysis to highlight visible differences in the impregnation of the anatomical tissues within the walls of bamboo culm internodes. *Dendrocalamus giganteus* culm was used for this purpose. There's a notable variation in vascularity and, consequently, porosity between the innermost parts of bamboo walls and those closer to the outer limits. In this case, samples were specifically taken from the inner third and the outer third, excluding the intermediate third. What can be observed is that the most prominent peak is situated between 200°C and 300°C, with the subsequent peak, which typically corresponds to plant tissue constituents in other samples, being diminished. These observed variations indicate changes in the proportion of material components in these two distinct layers. However, only a subtle difference is noted in the degradation temperature of the PCM, which doesn't clearly reveal variations in the quantity of this substance.

Fourier Transform Infrared Spectroscopy (FTIR) was utilized to identify functional groups primarily in plant fibers Rodrigues and Galzerani (2012), as well as chemical bonds in materials. The samples used were the same as those in the TG analysis, including raw PCM. The results are derived from the absorption of radiation at various wavelengths, spanning from 4000 to 500 cm^{-1} Fredericci, Ferreira, Oliveira and Pinto (2016), as depicted in Figure 13. Notably, the active peaks observed in all bamboo samples exhibit a striking degree of similarity, suggesting minor variations in intensity. Existing literature suggests that each absorbance band is associated with characteristic chemical

functional groups in specific materials, such as lignocellulosic substances Sánchez, Morales and Caicedo (2017).

Bamboo primarily consists of chemical elements like lignin, cellulose, hemicellulose, starch, silica, and pectin. According to Liu and Fei (2013), the bands between 1600 and 1450 cm^{-1} represent the characteristic region of lignin, hemicellulose, cellulose, and pectin, with peaks between 1558 and 1508 cm^{-1} indicating the presence of lignin, as well as peaks between 3338 and 1234 cm^{-1} .

Around 3000 cm^{-1} , low-intensity peaks are noticeable in the sample treated with PCM, linked to the stretching of $=\text{C}-\text{H}$ bonds in alkenes. These bonds exist in the polymers due to the butadiene monomer Guimarães et al. (2023). Two peaks at 2919 and 2850 cm^{-1} are related to the stretching of $\text{C}-\text{H}$ bonds in alkanes. These bonds are found in bamboo fiber components (cellulose, hemicellulose, and lignin), soluble extractives, and the polyurethane resin (PU) polymer structure, resulting in an increase in the intensity of these peaks in treated samples.

A peak at 1735 cm^{-1} is attributed to the stretching of $\text{C}=\text{O}$ bonds, associated with the acetyl ester and uronic acid groups in hemicelluloses or the ester linkage of ferulic and p-coumaric acid groups in lignin and/or hemicellulose Ferreira, Silva, Lima and Toledo Filho (2017). In samples without PCM, an increase in the intensity of these peaks is observed, likely due to the $\text{C}=\text{O}$ bonds of polymer carboxylic groups. However, in samples containing PCM, these peaks tend to decrease in intensity and shift slightly, possibly due to interactions between the PCM and $\text{C}=\text{O}$ groups present in bamboo components Guimarães (2023).

In the region between 1300 and 1000 cm^{-1} , some peaks related to the stretching of $\text{C}-\text{O}$ bonds can be observed, characteristic of alcohol, carboxylic acids, ester functional

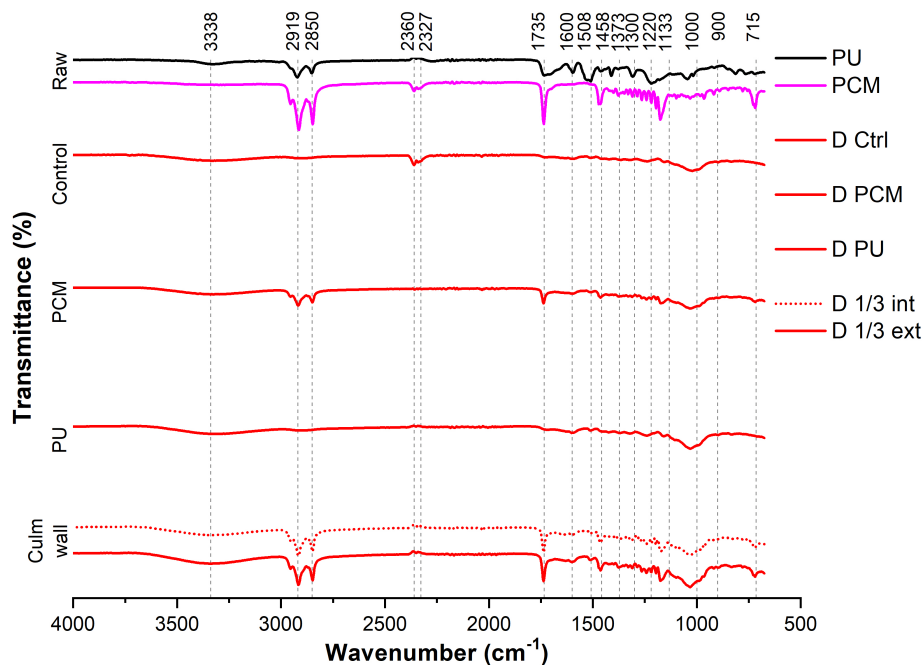


Figure 13: FTIR spectroscopy of raw bamboo (D Ctrl), PU (D PU) and PCM (D PCM), samples of the investigated specimens besides raw PCM and PU. Also, inner and the outer third of bamboo walls samples (D 1/3 int and D 1/3 ext).

groups, or ethers present in bamboo fiber components or the PU polymer. Between 1220 and 1133 cm^{-1} , there is a decrease in peak intensity in PCM-containing samples, potentially related to interactions between PCM and bamboo or polyurethane components.

Peaks at 900 and 896 cm^{-1} can be attributed to β -glycosidic linkages between xylulose units in hemicellulose. Bands between 1458 and 1373 cm^{-1} may indicate typical cellulose absorption. The peaks at 1630 and 1639 cm^{-1} are attributed to the stretching vibration of vibrations, signifying the presence of starch and H_2O , respectively Pedrangelo (2020).

As per Liew, Hamdan, Rahman, Rusop, Lai, Hossen and Rahman (2015), the band from 3200 to 3500 cm^{-1} (3338 cm^{-1}) typically indicates an increase in hydroxyl groups, and the 2921 cm^{-1} peak indicates polysaccharide CH. The 561 cm^{-1} peak suggests the presence of CBr, while the 1735 cm^{-1} peak indicates the C=O bond.

These findings collectively provide valuable insights into the chemical composition and structural attributes of the investigated bamboo samples and confirm that no significant chemical reactions occur during the impregnation process. Additionally, they help verify the presence of PCM in the samples.

4. Conclusions

This study represents a significant advancement in the exploration of processes that can facilitate the utilization of bamboo as a support material for PCM impregnation. In this research, bamboo culms are impregnated under negative pressure while maintaining their typical practical shape and

sealed with polyurethane resin to create a thermally efficient composite material. The thermal variation wind tunnel analysis highlights the material's ability to stabilize temperatures around the specific melting point of the PCM (24°C), underscoring its functionality. However, it also reveals that the current method of sample preparation may not fully maximize this capability.

The presence of increasing airflow demonstrates the samples' capacity to store thermal energy, but they are unable to entirely prevent this energy from transferring into the passive chamber used in the primary experiment, mainly because of the gaps contained in the samples. Nonetheless, it also indicates that heat exchange occurs in direct proportion to the wind speed.

Comparative studies involving conventionally employed materials in civil construction strongly emphasize the distinct behavior of PCM. Nevertheless, the comparison made with bamboo impregnated with coconut oil does not reveal a significant improvement in thermal efficiency that would qualify this alternative material for similar use as commercially manufactured industrial PCMs.

Furthermore, FTIR, TG, and DTG analyses indicate that no notable chemical reactions take place during the impregnation process, which is advantageous for its application in phase change thermal energy storage. This process ensures efficient penetration of the PCM into the porous structure of the bamboo culms. Consequently, the developed composite material holds promise as a versatile bamboo-based composite that serves multiple functions and has the potential for applications related to energy-saving in building thermal conditioning. It is anticipated to enhance the energy efficiency of buildings and other related purposes.

The results of this study also highlight the importance of conducting more comprehensive analyses regarding the possibilities of impregnating bamboo culms with PCMs. Other bamboo species with specific characteristics may offer more intriguing capabilities for this application. Additionally, different impregnation methods and thermal analysis techniques should be explored to assess potential process improvements.

CRedit authorship contribution statement

Fabício Rezende Fontenelle: Conceptualization, methodology, data curation, visualization, writing original.

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THIRD PART - CONCLUSIONS AND RECOMMENDATIONS

3.1. Achievements

- Prototypes of bamboo culms impregnated with PCM were developed using simplified methods throughout the process, resulting in a high PCM content and no excess leakage during heating and cooling cycles. The produced objects were proven to be functional.
- Fast, simple, efficient, and cost-effective methods for bamboo impregnation with PCM were created.
- Efficient, simple, and cost-effective methodologies for testing thermal variation with reevaluation and improvement were developed, including the insertion of airflow as analysis parameters through clever adaptations using available equipment.
- The variation in impregnation capacity and functionality of impregnated bamboo was confirmed with respect to the different species tested.
- The influence of the morphology of bamboo prototypes and their different species on the achieved thermal efficiency was demonstrated.
- The influence of bamboo density on the impregnation level achieved was confirmed.

3.2. General conclusions of the Thesis

This work, which was guided by concepts such as low-tech, smart materials and systems, self-production, and minimal processing, demonstrated the feasibility of using simplified technology and methodology for the production of objects that leverage the physical support capabilities of manufactured bamboo culms combined with the unique thermal capacity of the tested PCM, integrating these features in a functional manner.

In the first paper (Article 1) where this feasibility was initially tested, the results confirmed the temperature anchoring achieved by the object made from bamboo culms impregnated with *Philostachys aurea* species and PCM, within the specific temperature range of the commercial PCM used. It also verified the retention and subsequent storage of thermal energy as it passed through its materiality into the isolated and protected environment of the passive chamber, shielded from external temperature variations. This article also presented a simple and cost-effective experimental methodology developed and adapted in the laboratory for assessing the thermal behavior of samples when subjected to temperature variations. Through chemical and ultrastructural visual characterizations, the impregnation by PCM in the

samples was also confirmed, as well as the virtually inert chemical behavior of PCM within the bamboo composition. During this experimental campaign, the impregnation methodology used, also developed and adapted in the laboratory, involved the bamboo culm in its original cylindrical form being subjected to PCM suction by pumping, which proved to be efficient, clean, and easily executed, thereby minimizing excessive PCM wastage during this process.

In the second paper (article 2), when comparing four different bamboo species: *Bambusa tuldoidea*, *Dendrocalamus giganteus*, *Guadua augustifolia*, and *Philostachys aurea*, it was found that *D. giganteus*, with larger dimensions in terms of wall thickness, distance between nodes, and culm diameter and length, along with lower density, exhibited greater efficiency for the desired purposes in this work. When exposed to the thermal test, it demonstrated an even more significant temperature anchoring compared to the other species, particularly at the specific temperature of the tested PCM. It had also a higher PCM impregnation content in a larger volume of material, making it, at first, the best-qualified species among those studied. The relationship between the prior density of bamboo culms and their impregnation capacity was also confirmed in this experimental campaign. The methodology for evaluating thermal behavior was enhanced by forcibly reducing the temperature in the experimental setup through the addition of an active cooling chamber with ice, as well as an extra insulation layer using EPS panels, demonstrating an emphasis on ingenuity through simplicity and low cost without compromising functionality. As for the impregnation methodology, it was also improved by an immersion process in an environment subjected to negative pressure through vacuum pumping, resulting in a higher PCM content in the samples. Chemical and ultrastructural visual characterizations conducted confirmed PCM impregnation in the various species of samples, as well as the virtually inert chemical behavior of PCM within the bamboo composition.

In the third paper (article 3) of this thesis, the wind tunnel test demonstrated that the influence of airflow added to the system, where temperature variation is already occurring, significantly affects the rate of heat exchange. In this experiment, which was considered an improvement over the setup used in the previous experimental campaigns in the "hotboxes," the parameter of wind at three different speeds (measured on the sample surfaces) was added, consistent with the typical airflow rates that buildings are commonly exposed to in real weather conditions. This enhancement became possible through the adaptation of a setup originally used for other types of analysis, in which a closed circuit of air in a controlled environment with parameters such as temperature, airflow, and relative humidity is cyclically forced. In this

experiment, additional thermometers were added to the setup, allowing for the execution of two samples per experimental cycle, enabling better result comparisons (with only one "external air" temperature for each pair of samples) and time savings. The inclusion of conventional materials as samples in the tests of this campaign also allowed for better comparison of the absolute results obtained from the PCM-impregnated prototypes, helping to demonstrate their temperature anchoring and thermal energy storage capabilities once again. The addition of bamboo samples impregnated with coconut oil (which has melting and solidification temperatures compatible with conventional PCMs) opened up new possibilities for experimental campaigns to assess capabilities similar to industrially and commercially produced PCMs when compared. However, in this specific case, this material did not yield sufficiently promising results. The bamboo samples, both impregnated and control, made exclusively from the *Dendrocalamus giganteus* species, aimed to explore this species, which had shown the most suitable qualifications in the previous experimental campaign. The morphology of the samples, individualized as arched slats from culm sections with inherent irregularities due to the artisanal production methodology used, posed a potential problem. When exposed to temperature variation and wind, these samples did not efficiently block the airflow into the insulated environment (passive chamber), likely due to the excessive presence of gaps resulting from the rudimentary form they exhibited.

Throughout this entire process, it was believed that the maximum capabilities of the available laboratory infrastructure and research technology had been utilized. However, the gaps revealed through the research experience and presented as recommendations for future work also contribute to forming a critical scientific conceptual foundation for the development of the explored techniques.

It is the expectation of this work that the suggestions provided here will enable the pursuit of even more promising results.

3.3. Recommendations for future work

The studies that require further investigation and could not be carried out, either due to budget constraints, lack of access to technologies and techniques, equipment, or time constraints, particularly to be highlighted, are as follows:

Botanical and impregnation issues:

1. Testing other bamboo species, given the various available and abundant ones, as PCM reservoirs.

2. Locating in the porosity of bamboo's anatomy where there is greater or lesser PCM impregnation and why, taking into account that for laminates and industrially made bamboo-based objects, some sections or tissues are more advantageous than others.

3. Testing new possibilities for impregnation equipment and processes, such as the use of positive pressure in an autoclave.

4. Testing different bamboo curing stages at the time of impregnation to verify the possibility of its expansion.

5. Testing other pre-treatment methodologies for impregnation to increase its capacity.

6. Testing other lignocellulosic plant species as PCM reservoirs to establish comparisons and deepen knowledge in the field.

PCM issues:

1. Seeking low-cost and readily available alternative PCMs for use, taking into consideration the necessary qualities for effective utilization in this system that utilizes the porosity of plant tissues, especially materials from the Brazilian agroindustry that are either discarded or low-cost.

2. Testing the relationship between the porosity of plant tissues and any changes in PCM operation concerning thermal qualities like phase change temperature and enthalpy due to capillarity effects.

Engineered materials issues:

1. Testing the production of other types of material processing, especially those more suitable for use in building envelopes, both for roof and wall construction, as well as for coatings such as ceilings and interior layers that can contribute to the environmental comfort of indoor spaces, such as cross-laminated glued bamboo, among others.

2. Testing with other morphological structures of bamboo, such as mats, in the formation of composites with materials like cement, for example.

Other tests:

1. Testing reduced-scale prototypes and subsequently full-scale construction for real use (1:1), seeking climate and execution conditions as realistic as possible.
2. Testing for both vertical (masonry) and horizontal (roofs) closures.
3. Testing durability trials with repeated cycles of phase change to check for loss of thermal storage capacity or other effects.
4. Conducting ultrastructural microscopic imaging of impregnated bamboo at high magnification.
5. Conducting mechanical tests on bamboo impregnated with PCM to check for loss of strength.
6. Conducting accelerated aging tests and UV exposure tests."

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