12th World Bamboo Congress

Taiwan, 18-22 April, 2024

www.worldbamboo.net

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 byhigh-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 utilizedas 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 werecomparatively analyzed: raw culms, culmssealed with polyurethane resin (PU), and impregnated with PCM also sealed with PU. The production proceesssought 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 itsliquid 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 arederived 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."

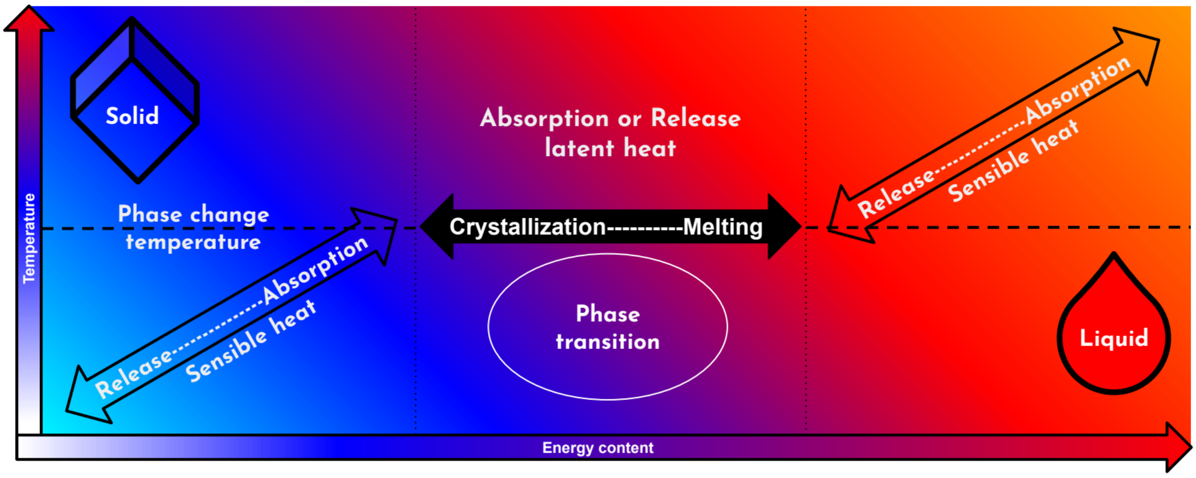


Fig. 1. Energy content x temperature - the behavior of PCMs.

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 coolingof 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 isoften 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.

Phyllostachysaurea	**Objective**	**Denomination**
Raw bamboo culm - withouttreatment	control	Control
Bamboo culmsealedwith PU	analysis1	PU
Bamboo culmimpregnated 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 standardNBR 16828-2(ABNT 2020). The selection criteria were primarily based on factors such asthe 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 bamboostalks 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 chamberfor the hotbox essay. These prepared specimens were then placed in an oven for induced drying, following established procedures documentedin 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 liquidstate due to the ambient temperature exceeding 24°C.

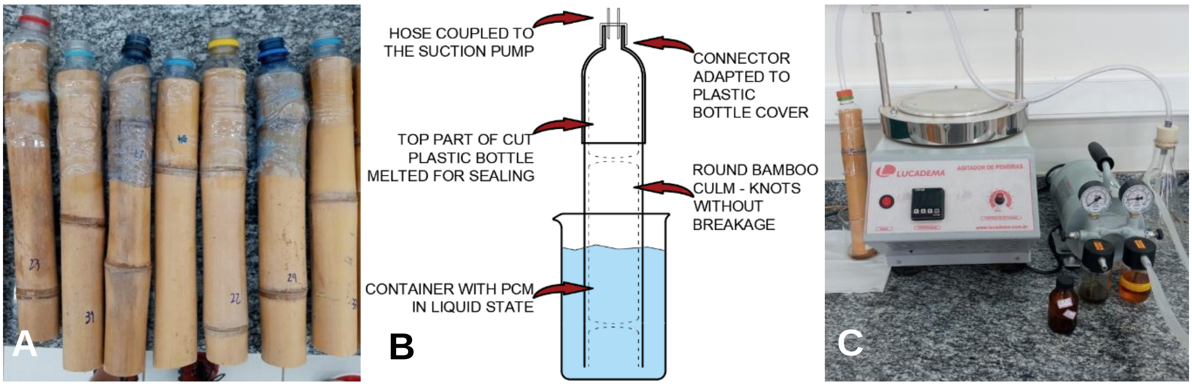


Fig. 3. Used system for impregnating round bamboo culms by vacuum pumping. (A) Culms with plastic bottles adapted at the end for sealing and suction, (B) Diagram of the impregnation scheme, (C) Impregnation setup in operation.

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.

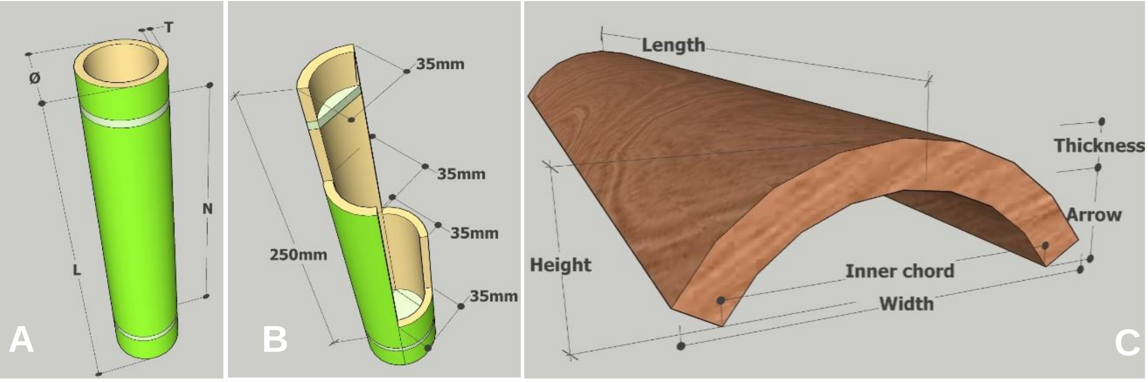


Fig. 4. The original shape of the sample from the impregnation process is depicted in (A), and (B) illustrates the schematic of the longitudinal cut of the stalks followed by the expected final shape(C).

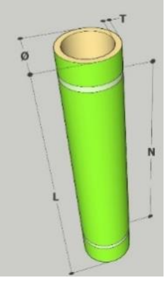
The sealing or coating process was carried out by mixing the components of the PU resin and depositing the test specimens onto a suitable support for manual painting using a common commercial brush (Figure 5). This process demanded swift execution due to the short drying time of the product. The PCM-impregnated samples had to be sealed within the controlled environment of an acclimatization chamber, where controlled humidity and temperature levels were maintained, approximately around 19°Cwith 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 general dimensions(mm)**			**Average characteristics of the nodes**		
	Diameter Ø	**Length L**	**Wall thickness T**	**Amount**	**Averagedistance (mm) N**	
Phyllostachysaurea	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.

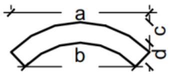
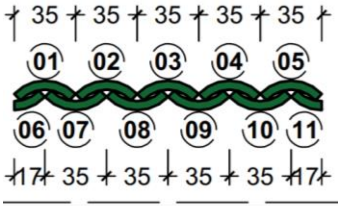
The determination of apparent density was calculated as the ratio between the dry mass (weighed using a precision scale following oven drying) and the water-saturated volume (determined using the displaced liquid method based on Archimedes' principle), while considering the irregular shape of the samples(Forest Products Laboratory (US). Laboratory 2010; Moreschi 2005). Themass 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 presentedin Table 3.

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

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

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 surfaceof the active chamber's boxas 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, anEPS-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.

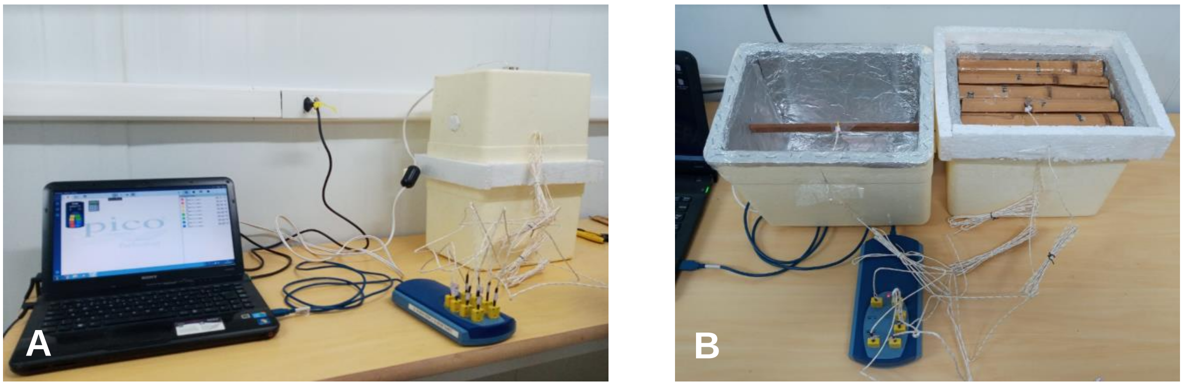


Fig. 6. (A) The Hotbox essay setup in operation and the arrangement of samples and thermocouples in the thermal box (B).

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 asfollows:

- 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.

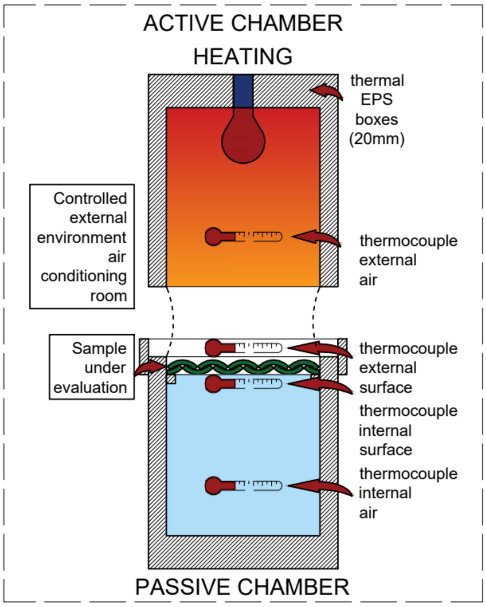


Fig. 7. Schematic diagram of the Hotbox setup with the location of the thermocouples.

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 approximately40 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 wereplaced inthe 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/cm^3)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.*

Averagemoisturecontent(%)		Mediumweight(g)			Apparent basic density (g/cm³)	Average mass increase after impregnation by PCM and application of PU resin	
Original	**Post ovendrying**	**Original**	**Post ovendrying**	**Loss(%)**	**Original**	**PCM**	**Resina**
29	11	137	125	8,76%	0,72	7,11%	5,29%

3.2. Hotboxessay

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
External Air	EA
ExternalSurfaceof sample	ES
Internal Surfaceof sample	IS
Internal Air	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.

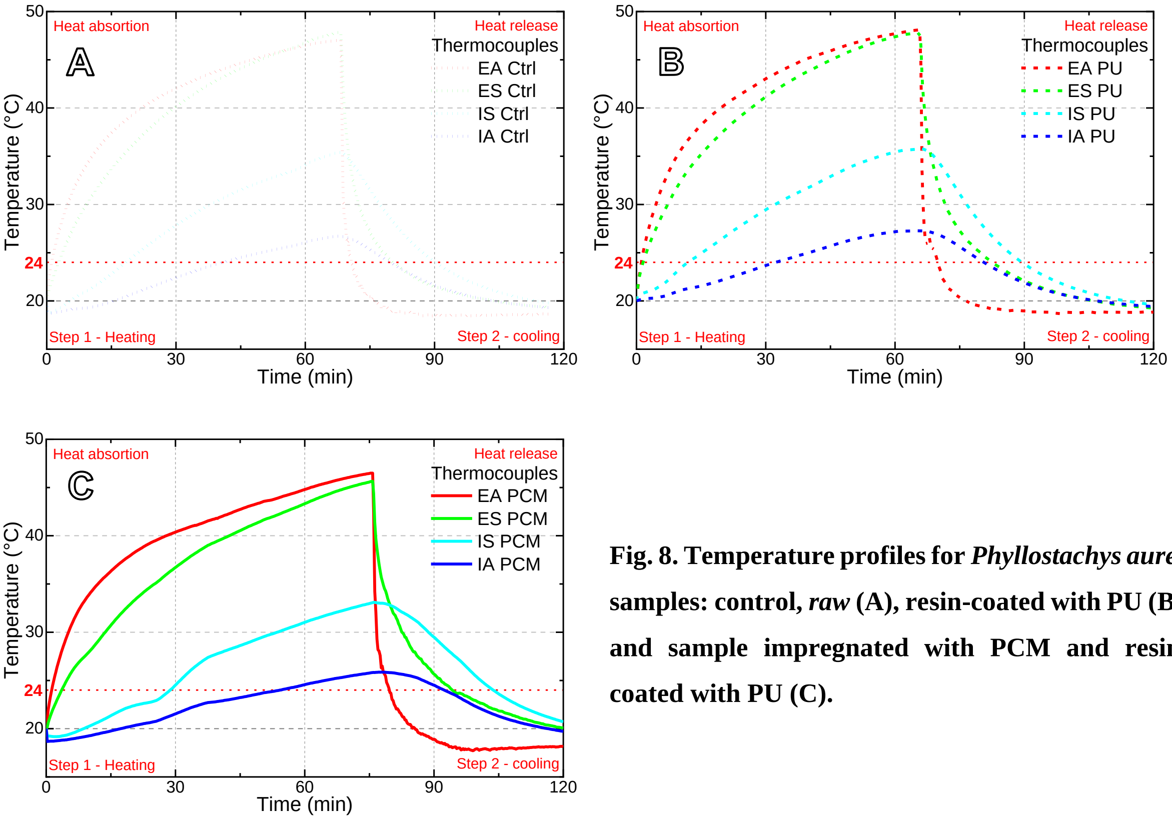


Fig. 8. Temperature profiles for *Phyllostachys aurea* samples: control, *raw* (A), resin-coated with PU (B), and sample impregnated with PCM and resin-coated with PU (C).

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.

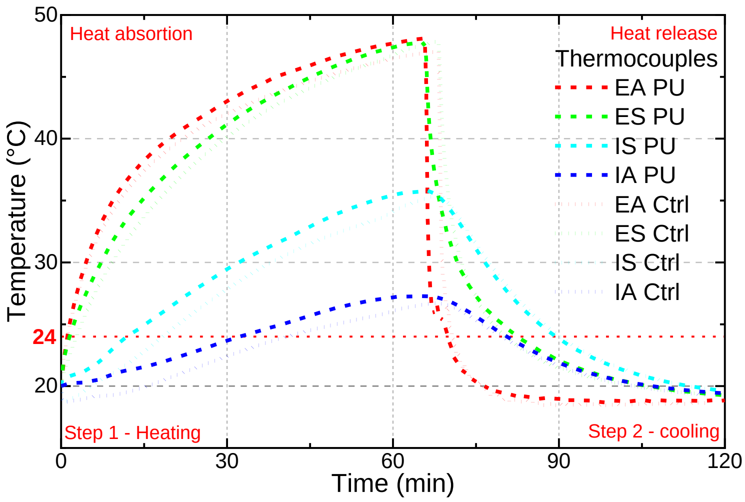


Fig. 9. Combined temperature profiles for sample raw (control), compared to resin-coated with PU sample.

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.

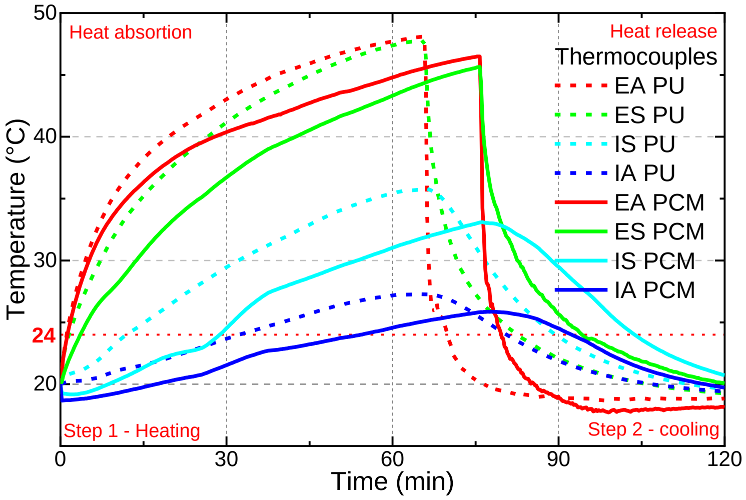


Fig. 10. Combined temperature profiles for sample resin-coated with PU, compared to sample impregnated with PCM and resin-coated with PU.

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.

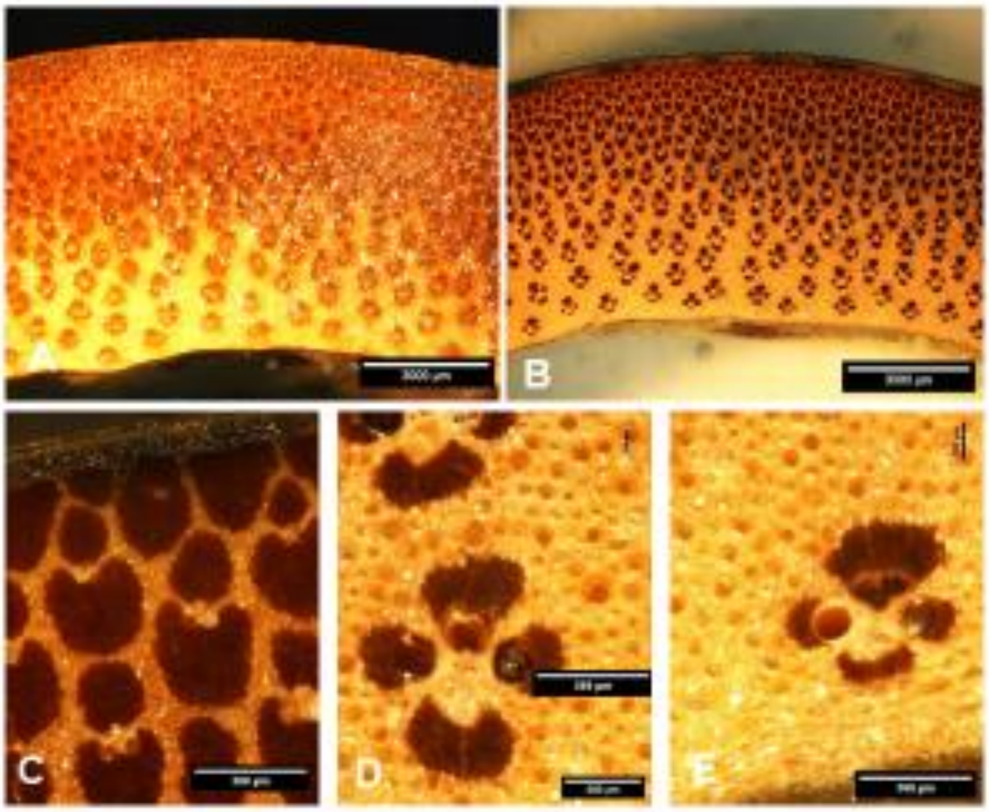


Fig. 11. Images obtained by optical microscopy (at 10x magnification) of the internodal cross-sections of *Phyllostachys aurea* bamboo culm with PCM impregnation (A) and without impregnation (B), and an images at 125x magnification of the same transversal cut of de outer (C), mid (D) and the inner part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

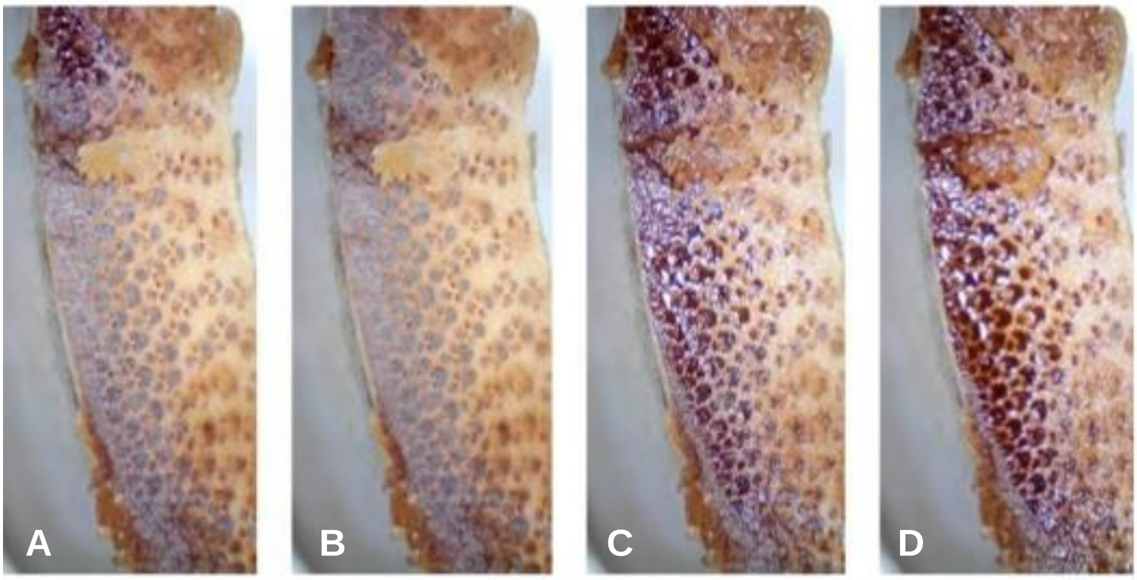


Fig. 12. Successive images on a macroscopic scale extracted from the melting process of PCM24 impregnated in *Phyllostachys aurea* bamboo culms, taken every 20 seconds from the 20s (A), 40s (B), 60s (C), to 80s (D).

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.

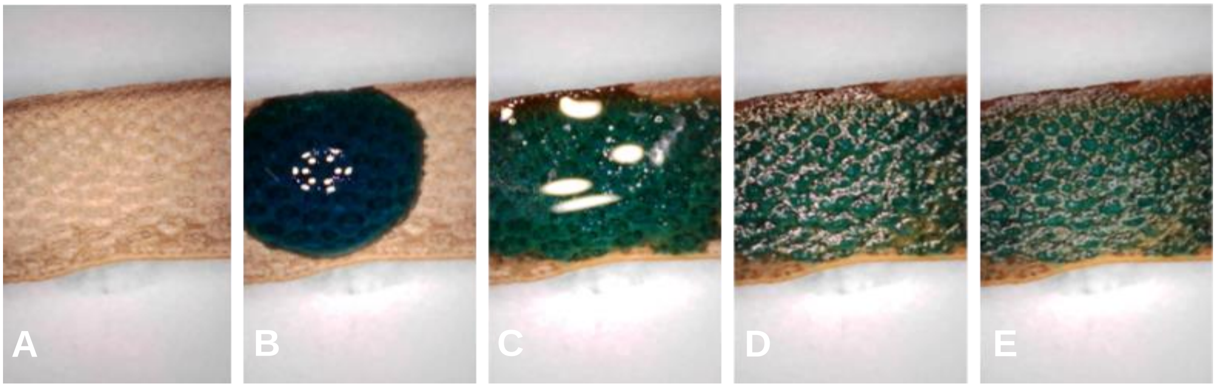


Fig. 13. Successive images on a macroscopic scale of the bamboo *Phyllostachys aurea* dye impregnation process, chronologically taken every 20 seconds from 0s (A), the 20s (B), 40s (C), 60s (D) to 80s (E).

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.

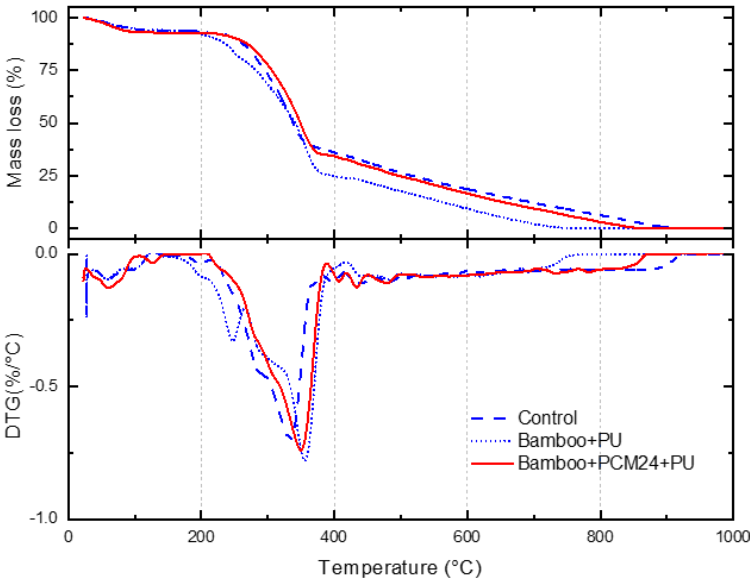


Fig. 14. Thermogravimetric analysis curves: TG and DTG of raw culm of *Phyllostachys aurea*, treated with PU and PCM.

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 =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 stretchingof C-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 stretchingof 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 et al. 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 et al. 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 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 H2O, 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.

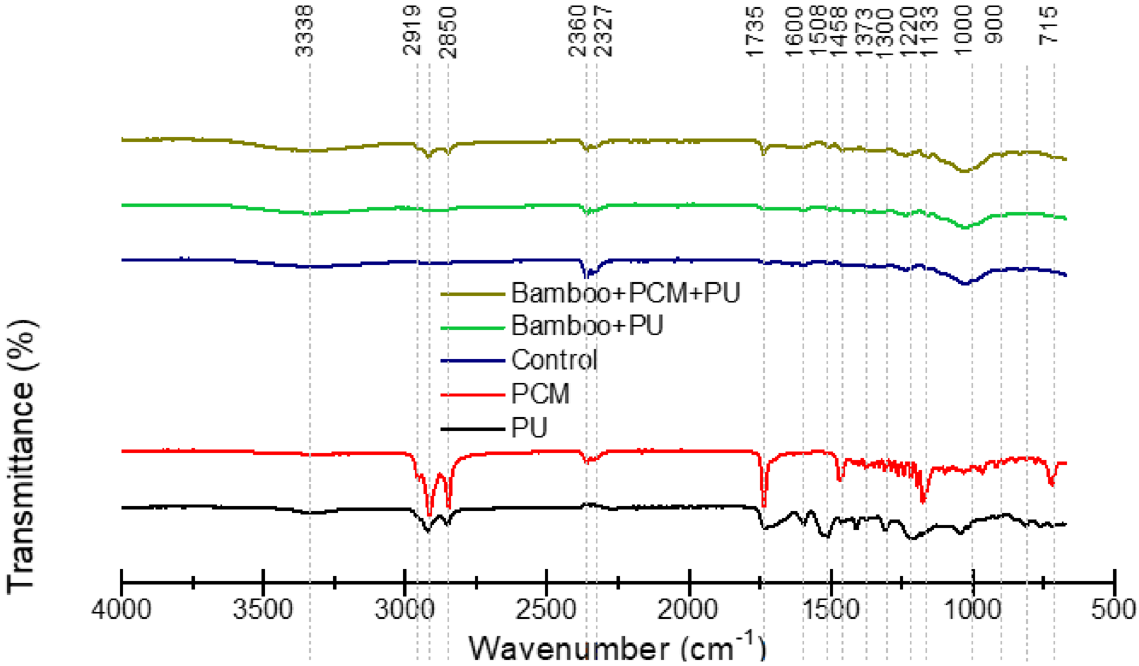


Fig. 15. FTIR spectroscopy of raw culm of *Phyllostachys aurea*, treated with PU and PCM, and samples with raw PCM and PU.

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

The authors are grateful to the Universidade Federal de Lavras. Department of Engineering and PPGCTM - Department of Forest Science, and also to theUniversidade Federal de Juiz de Fora, Federal, MG, Brazil.

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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