



Turning Invasive *Cortaderia Selloana* into Sustainable Building Insulation: A Biomass Valorization Approach

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Abstract

Cortaderia selloana (pampas grass) is an invasive species in Europe, North America, and Oceania, native to southern South America. Its widespread distribution has contributed to biodiversity loss, increased landscape management costs, and public health concerns. At the same time it leads to challenges in control measures. Furthermore, limited research exists on the species' potential for creating a value chain from its biomass. This study investigates the potential use of *C. selloana* stems as a thermal insulation material for building applications. The methodology involved laboratory testing, including measurements of moisture content (9,24%), water absorption by capillarity, linear retraction, contact angle (hydrophobic exterior and hydrophilic interior), Fourier-Transform Infrared Spectroscopy coupled with an Attenuated Total Reflectance accessory (ATR-FTIR) and Optical microscopy observations, which confirmed a porous structure and waxed external walls, supporting insulating performance. Furthermore, thermal analysis results indicate that the stems provide thermal insulation comparable to cork and wood fibre panels, with a thermal conductivity of 0.04 W/mK, and good mechanical resistance, with strong flexural resistance (6.85 MPa), with high elasticity. In conclusion, the findings suggest that *C. selloana* stems offer promising attributes as a sustainable building insulation material and also as a reinforcing component in bio-based composites for various applications.

Keywords *Cortaderia selloana* · Invasive species · Pampas grass · Thermal insulation · Sustainable building material · Biomass valorization

Introduction

The Pampas grass, or *Cortaderia selloana*, is a large perennial herb recognised as Angiospermae, which encompasses flowering plants and monocotyledons, as it possesses a single seed leaf [1]. The species belongs to the order *Poales* and the *Poaceae* family (*Gramineae*). The genus *Cortaderia* consists of herbaceous perennial plants, given that name because of their cutting leaves, as the word “*cortar*” comes from the Spanish “to cut” [2].

Pampas grass disperses its seeds through the air, with a single plant capable of producing up to one million seeds, approximately 90,000 to 100,000 seeds per seed head [3]. The hermaphroditic specimens act as pollinators for female specimens to produce seeds. They reach reproductive maturity at around 1 to 3 years old and can live for at least eight years, with the longest recorded lifespan being up to 40 years [3].

Native to southern South America, namely Argentina and Brazil, *Cortaderia selloana* became an invasive alien species in many regions, such as North America, Oceania, Africa and Europe. In the European context, it is widespread in Portugal, Spain, France, Italy, the United Kingdom, the Netherlands and Belgium [4]. Due to this high risk of invasive behaviour, the species was classified at level 26 [5, 6], a value obtained through a protocol adapted from the Australian Weed Risk Assessment [7], where values above 13 indicate a higher risk of invasive behaviour in Portugal [5]. Despite the high risk of invasive behaviour and its presence all over the territory,

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Cortaderia selloana was only listed for the first time as an invasive species in Portugal in Decree-Law No. 92 of 2019.

Domènech et al. [8] identified which lands were most susceptible to the invasion of the species and which components could trigger uncontrolled reproduction. The authors concluded that the presence of *Cortaderia selloana* declines as the distance from urban areas increases and accentuates in abandoned sites and pasture areas (Fig. 1). Figure 1 illustrates the species in an urban setting. Many of the sites that stand out for invasion are those that served as pasture in the past, meaning they lost their native vegetation long ago, and those that had suffered several changes in land use over time, such as interstitial areas of highways and abandoned urban areas. Thus, it can be stated that invasion patterns can be explained by the historical legacy of land use changes [8]. The predictions show that the expansion of the species is increasing due to climate change and urbanisation, once native vegetation is being displaced by human activity [9].

Nonetheless, according to Liendo et al. [10], *Cortaderia selloana* is not as widespread in Central or Northern European countries, which might create conflicts of interest within the Union. As stated by Brundu et al. [11], about 20 to 25 million plants are being cultivated at European nurseries, leading to a market value of about 200 million euros annually. Liendo et al. [10] highlight the need for more actions from the European Union to prevent the spread of the species, highlighting its impact on human health.

Regarding this impact, until recently, only skin cuts by sharp leaves were mentioned [12] and pollen allergenicity has only been suggested but not confirmed. Rodriguez et al. [12] conducted a pioneering study on *Cortaderia selloana* risks to public health and concluded that grass allergy season in Western Europe might be extended due to the presence of the plant.



Fig. 1 *Cortaderia selloana* field in an urban setting

The economic impact of managing invasive species is substantial. In Europe, the costs are estimated to have reached €116.61 billion between 1960 and 2020, with 60% of this amount attributed to damage across multiple sectors [13].

Also, as global temperatures continue to rise the species may occupy an even larger area. According to Tarabon et al. [14], their models indicate this species' northward and eastward expansion under future climates despite already occupying substantial regions along the western and Mediterranean French coasts. They categorise *Cortaderia selloana* as a 'climate warming winner', suggesting that Europe and the Mediterranean region could become suitable for the species' establishment under any warmer scenario.

On the other hand, with the rise of extreme weather conditions due to global warming, a significant concern in the construction sector is to reduce greenhouse gas emissions by enhancing buildings' energy efficiency, minimizing operational carbon, and decreasing embodied carbon along with other environmental impacts simultaneously [15]. Bio-based materials and the exploration of invasive species present a promising alternative to conventional insulation due to their lower environmental footprint and ability to sequester carbon. Invasive species, such as *Cortaderia selloana* and other fast-growing plants such as reed and straw, can absorb significantly more carbon than traditional tree species in a short period, making them an alternative for sustainable building materials [16, 17].

Recent research has increasingly highlighted invasive species' potential as a viable resource for sustainable construction. Studies show that *Arundo Donax* reeds, considered an invasive species in Europe, hold promise as an insulation building material, already used in vernacular architecture [18, 19]. Similar species, such as bamboo, were further studied as biocomposites in polymers and found to improve tensile and flexural mechanical properties [20].

Pittau et al. [21] examined an insulation composite of *Lagarosiphon major* and mycelium, finding that its hydric and thermal properties match those of other bio-based materials. Other invasive species' composites were also found to have a promising outcome as building materials, such as *Pontederia Crassipes* for sound absorption and insulation [22] and wood chips from invasive species, such as *Pinus* species, as an alternative for sand and gravel as aggregates for bio-concrete [23]. Pattnaik et al. [24] reviewed physico-mechanical properties and applications of grass fibre-reinforced composites, among them *Cortaderia Selloana* fibres, concluding that biocomposites are recognised as key materials in the transition toward sustainability. Fibre-reinforced composites

can be applied in diverse fields, ranging from packaging to furniture, offering mechanical strength and biodegradability without the use of harmful chemicals [25].

Additionally, using bio-based materials in construction is vital for reducing embodied carbon emissions, thereby contributing to the EU's decarbonisation targets. In this context, this paper aims to investigate the potential of *Cortaderia selloana* stems as an insulation material in the construction industry, proposing a use for an underutilised biomass. Although several natural fibres have been explored for thermal and acoustic insulation, no studies have assessed *Cortaderia Selloana* for this purpose. Additionally, the species' culm structure naturally contains longitudinal air-filled cavities and a fibrous cellular matrix, which are key features for insulation materials. The novelty of this work lies in the first systematic evaluation of *Cortaderia Selloana* stems as an eco-friendly insulation material, linking invasive species management with sustainable building solutions.

Materials and Methods

Cortaderia Selloana stems were chosen for practical reasons: they represent a significant volume of the plant, it is easy to collect, with minimal processing procedures, and their hollow morphology already contributes to insulation as the trapped air adds to low thermal conductivity. Furthermore, stems can be gathered into reed-like panels, similar to commercial *Hiss-Reet* panels, which consist of rigid boards to provide thermal insulation.

No pretreatment was made to the fibres, as although it could modify properties such as hydrophobicity or density, it would also increase processing costs, energy demand and environmental impact. Thus, this work

focused on assessing the raw culm biomass as a baseline material.

The tests performed on samples of *Cortaderia selloana* include moisture content, water absorption, linear retraction, Fourier-Transform Infrared Spectroscopy coupled with an Attenuated Total Reflectance accessory (ATR-FTIR), Optical microscopy observations, water contact angle, mechanical strength, and thermal behaviour analysis conductivity. These tests were selected to assess the species' material properties and potential use as an insulation material.

Figure 2 presents the stems selected for analysis.

During the harvest process, notable differences were observed between two collection periods, namely October and February. The February samples appeared more fragile and damaged, with some showing signs of rot, in contrast to the October harvest, where the stems were more rigid and robust. Additionally, the October samples contained more water, as thicker stems released a significant amount of water when cut, whereas the February stems appeared much drier. This is likely due to the natural growth cycle of the species, as *Cortaderia selloana* reaches the end of its growth, flowering, and seed dispersal cycle in October, while in February, it undergoes senescence.

To prevent the further spread of this invasive species, non-dissemination principles were strictly followed during both harvests, adhering to the best practices manual from the STOP Cortaderia project [26]. Seed plumes were bagged to avoid seed dispersion during handling.

After harvesting, the samples were stored vertically in a well-ventilated environment with controlled conditions (temperature: $20\text{ }^{\circ}\text{C} \pm 5$, relative humidity: $40\% \pm 5$) to allow natural drying before testing.



Fig. 2 *Cortaderia selloana* stems. **(a)** Cross-section on various parts. **(b)** Longitudinal section

Moisture Content

The methodology followed the ISO 18134-2:2017 standard for the moisture content determination, which refers to *Solid biofuels – Determination of moisture content – Oven dry method – Part 2: Total moisture – Simplified method* [27]. A total of 24 samples were collected from two different harvest periods. Twelve samples were collected in October 2022, with six samples having an average diameter greater than 12 mm (Group A1) and six with an average diameter smaller than 12 mm (Group A2). Another twelve samples were collected in February 2023, similarly divided into six samples greater than 12 mm (Group B1) and six smaller than 12 mm (Group B2). Additionally, 14 control samples (Group C), consisting of samples from the first harvest period, were prepared for the repetition of some tests during the following week.

The test involved drying the samples in an oven at 103 ± 2 °C until they reached a constant mass. Each sample was identified, measured, and weighed before undergoing drying. Weights were recorded at 30 min, 2 h, 4 h, and 24 h intervals. The moisture content was calculated using Eq. 1.

$$MC = ((m_0 - m_1)/m_1) \times 100 \quad (1)$$

where MC is moisture content; m_0 is the wet mass in grams; and m_1 is the dry mass, in grams.

Weights were recorded at specific intervals to ensure accurate determination of moisture loss. A balance was used for weighing the samples, and a water reservoir was available for saturation purposes.

Water Absorption by Capillarity

The water absorption test was conducted following the ISO EN 1609:2013 standard [28]. Samples from both harvest periods, designated as Groups A and B, were used for this test. The samples were placed vertically in a tray with a 5 mm layer of water to evaluate capillary water absorption.

The absorption of water through capillarity was calculated using the difference between the wet mass, which had one surface in contact with water for a specific time, and the dry mass, divided by the surface area that was in contact with water, according to Eq. 2.

$$A_i = (m_i - m) / a \quad (2)$$

where A_i is the absorption rate; m_i is the wet mass in grams; m is the dry mass, in grams; and, a is the surface area that was in contact with water in mm^2 .

The samples were weighed at 24 and 48 h to assess their initial water uptake. Afterwards, the samples were fully immersed in water for 96 h to achieve total saturation, and their weight was measured again to determine the maximum water absorption capacity.

In addition to Groups A and B, control samples from Group C underwent the same procedure, with more frequent weight measurements taken during the initial hours of the test, specifically at 15, 30, 60, 90, 120, 150, 180, 210, 240, 300, 360, 1440, and 2880 min. This allowed for a more detailed understanding of the water absorption curve during the early stages of the capillarity process.

Linear Retraction

The linear retraction test was performed to assess the dimensional stability of the samples during the drying and saturation phases, following the Portuguese standard NP 615 – Determination of shrinkage, which specifies methods for determining linear shrinkage and swelling in wood and wood-based materials.

The test consisted of determining the variation in the studied dimensions after saturation and drying. Linear retraction (ε) was calculated using Eq. 3.

$$\varepsilon = ((l_1 - l_2)/l_3) \times 100 \quad (3)$$

where ε is the linear retraction; l_1 is the saturated specimen dimensions in millimetres; l_2 is the air-dried specimen dimensions, in millimetres; and, l_3 is the oven-dried specimen dimensions, in millimetres.

Attenuated Total Reflectance Fourier Transform Infrared Spectroscopy (ATR-FTIR) Analysis

The Fourier-Transform Infrared Spectroscopy, coupled with an Attenuated Total Reflectance accessory (ATR-FTIR), aimed to examine the biochemical composition variations between the layers of the stem. The analysis was conducted using the infrared method by Fourier transform (FTIR) in a Shimadzu Fourier Transform Infrared Spectrophotometer IRAffinity-1 S (Kyoto, Japan).

This analysis aimed to identify the chemical composition and functional groups present in the samples. The methodology followed established FTIR practices for solid biomass materials, using a spectrometer to record the absorption spectra. This technique allows for detecting specific bonds and molecular structures based on the infrared light they absorb.

Ten samples, from different regions of the stem, were cut and prepared as films for spectral analysis. Each sample was scanned in the mid-infrared region, between

4000 and 400 cm^{-1} , to detect the characteristic peaks corresponding to organic compounds, such as cellulose, hemicellulose, lignin, and other minor constituents. The spectra were collected using 45 scans with a resolution of 4 cm^{-1} in transmittance mode.

Specific peaks were analyzed to identify relevant functional groups, such as hydroxyl (-OH), carbonyl (C=O), and ester (C-O) bonds. The FTIR spectra obtained were compared with known reference materials to assess the presence of specific compounds. The analysis specifically targeted differences between the inner and outer stem layers to understand the composition of both the fibrous core and the waxy outer cuticle.

Optical Microscopy Observations

Optical microscopy observations were conducted using a Leica Microsystems Binocular DM750 M Microscopy with a high-definition digital camera attached. This analysis aimed to examine the microstructural characteristics of different regions of the *Cortaderia selloana* stems. Samples were taken from three distinct parts of the stems: the smooth and shiny outer layer, the denser structure of the node, and the softer internal regions, including internal structures.

The samples were carefully prepared and mounted for observation under the microscope. Images were captured to document the microstructural differences between the outer cuticle, node, and internal fibrous material. This analysis provided insights into each part's structural organization and composition, which is essential for understanding their respective roles in the stem's mechanical and functional properties.

Water Contact Angle (WCA)

The water contact angle measurement assessed the hydrophilic and hydrophobic properties of different parts of the *Cortaderia selloana* stem. The tests were performed using the OCA contact angle measuring device from Dataphysics. Water was used as the test liquid, dispensed via a 500 μL Hamilton syringe at a dosage rate of 2 $\mu\text{L/s}$. Measurements were taken on the outer layer of the stem, the interior, and the denser node region.

The analysis aimed to determine how water interacts with these surfaces by measuring the contact angle between the water droplet and the surface. This provided insights into the wettability of each area, helping to understand their potential behaviour in various applications.

Mechanical Analysis

The mechanical properties of the *Cortaderia selloana* stem were evaluated using a Hounsfield Universal Testing Machine (UTM), a dynamometer designed explicitly for precise mechanical testing. Both flexural and tensile tests were performed to assess the material's bending and tensile strength. The UTM was equipped with sensitive load cells to measure the forces applied during the tests.

In the flexural tests, a three-point bending configuration was used, where the samples were supported at two points, and a force was applied at the midpoint. The span length, between the supports and the loading rate, was adjusted based on the sample size to ensure accuracy. For the tensile tests, the stems were clamped at both ends and stretched at a controlled rate until ruptured. The UTM recorded detailed data on the applied force, elongation, and deformation throughout both tests.

Flexural strength tests were carried out with a load cell capacity of 250 N, under a displacement range of 50 mm, test speed of 10 mm min^{-1} , span length of 100 mm, and an approach speed of 25 mm min^{-1} . Tensile strength tests were performed with a 1000 N load cell, under a gauge length of 100 mm, extension range of 50 mm, and test speed of 10 mm min^{-1} , with a preload of 10 N.

Thermal Insulation Testing

The thermal behaviour of *Cortaderia selloana* stems was assessed through a thermal conductivity test analysed using a custom-built hotbox designed and built in the Laboratory of Physics and Construction Technologies at the University of Minho. The setup was built following the ASTM C1363 standard [29], which specifies procedures for measuring heat transfer through building materials using a guarded hotbox. The apparatus consists of two chambers (hot and cold), each with a 1 m^3 internal volume.

The hot chamber is equipped with a heat source controlled by a temperature regulator, maintaining the temperature at 35 ± 3 $^{\circ}\text{C}$, while the cold chamber is kept at a constant 18 $^{\circ}\text{C}$. The hotbox is well-insulated with a 20 cm thick extruded polystyrene (XPS) envelope, providing a thermal resistance value of 5.71 $\text{m}^2\text{K/W}$.

The data collected from these tests were treated according to the ISO 9869 standard [30], for determining the thermal resistance (R-value) of building materials. This value was calculated using Eq. 4 outlined in the standard.

$$R = (T_{si} - T_{se})/q \quad (4)$$

where R is the thermal resistance, q is the heat flux density, T_{si} and T_{se} stand for the temperature of the internal surface and temperature of the external surface, respectively.

The R-value depends on the thickness of the material or solution. To calculate the thermal conductivity coefficient, Eq. 5 was used.

$$\lambda = e/R \quad (5)$$

where λ is the thermal conductivity, e is the thickness of the sample, and R is the thermal resistance.

The thermal analysis was performed using Greenteg gOMS II. This equipment consists of temperature sensors and surface temperature sensors positioned on both sides of the hotbox, along with a heat flux sensor to evaluate the rate of heat transfer through the samples. The data is recorded through a datalogger with a 10-minute interval and an accuracy of ± 0.1 °C for temperature measurement and $\pm 3\%$ for heat flux measurement. To minimize potential interference in the results, a high thermal conductivity tape was used to ensure optimal contact between the sensors and the sample surfaces. The data obtained from the Greenteg gOMS II provides instant results for the thermal resistance (R-value) and thermal transmittance (U-value) of the samples, calculated under the referenced standard. This setup allowed for precise measurement of the thermal properties of the stems, including their resistance to heat flow under steady-state conditions.

Results

The following section presents the key findings from the experimental tests conducted on *Cortaderia selloana* stems.

Moisture Content

The moisture content of the *Cortaderia selloana* stems was determined following the ISO 18134-2:2017 standard, as described in the materials and methods section. A total of 38 samples were analysed, with results for each group calculated based on the difference between wet and dry masses. The results are summarised in Table 1 below.

The average moisture content for the samples collected in October was as follows: Group A1 (stems with a diameter greater than 12 mm) had an average moisture content of 9.68%, and Group A2 (stems with a diameter smaller than 12 mm) recorded an average of 9.32%. For the February samples, Group B1 initially showed an unusually high average moisture content of 59.25%, which was likely due to residual environmental moisture at the time of testing, due to their thickness and shorter drying period, as this test was carried out in June of the same year. As this result was considered an outlier, Group B1 was excluded from the final analysis. Group B2, consisting of stems smaller than 12 mm, had an average moisture content of 8.80%.

The last 14 control samples (Group C), collected from the first harvest period, had an average moisture content of 9.16%, consistent with the results from the other groups. After excluding the outlier Group B1, the overall average moisture content across all samples was 9.24%, demonstrating stable moisture characteristics across the harvest periods.

Water Absorption by Capillarity

The water absorption test was conducted at an ambient temperature of $25 \text{ °C} \pm 3$, with a relative humidity of $55\% \pm 2$. The water temperature was maintained at 22 °C . Figures 3 and 4 show the test setup and samples after the test period.

The graph represented by Fig. 5 shows the results for Groups A and B as no significant differences were observed in water absorption during the capillarity phase and total immersion.

For Group A, the average water absorption was 0.014 g/mm^2 during the first 24 h, increasing to 0.018 g/mm^2 after 48 h. Following full immersion, the samples absorbed an average of 0.064 g/mm^2 . Group B samples, excluding those from subgroup B1 due to their high initial moisture content caused by insufficient drying time, showed average values of 0.016 g/mm^2 for the first 24 h, 0.021 g/mm^2 after 48 h, and 0.055 g/mm^2 following full immersion.

Figure 6 illustrates the capillarity water absorption for the Group C samples.

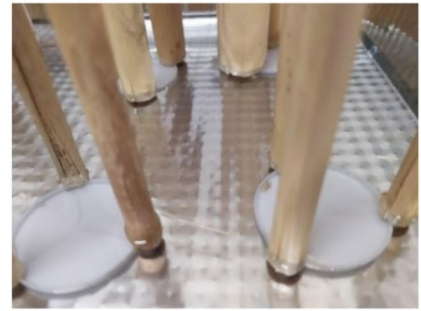
Table 1 Linear Retraction percentage values per diameter and length

SAMPLE GROUP	MOISTURE CONTENT (%)
Group A1	9,68%
Group A2	9,32%
Group B1	59,25%
Group B2	8,80%
Group C	9,16%
General average moisture content (excl. group B1)	9,24%

Fig. 3 Groups A and B samples during water absorption by capillarity test



(a)



(b)



Fig. 4 Group C samples after 96 h on water absorption by capillarity test

In Group C, the water absorption was highest during the first 4 h of the test, as anticipated. After the 24-hour mark, the absorption rate slowed significantly, indicating a steady state of water uptake. This gradual stabilization confirmed that the initial hours of contact are critical for water absorption. Specifically, Group C values reached

0.024 g/mm² within the first 24 h, 0.030 g/mm² after 48 h, and 0.038 g/mm² after 96 h, without total immersion. The test was stopped at this point, as the tendency toward stabilisation was already confirmed.

Including the control group (C) in the test was particularly valuable as it reinforced the observation that the first hours of water exposure are crucial for capillary absorption.

Linear Retraction

Unlike conventional materials, which typically exhibit shrinkage during drying and expansion upon saturation, the samples in this study displayed an initial expansion of their outer layers during the drying process. This expansion occurred due to the delamination of the outer layers. Upon saturation, the samples returned to dimensions closely resembling their original state, with some minor variations.

The samples were measured, using a digital calliper to ensure precision, in three different conditions: first in an air-dried scenario, then after being oven-dried at 103 °C, and finally after 48 h of saturation in water. Sample results from group B were discarded as the results were mainly

Fig. 5 Groups A and B2 samples behaviour during water absorption by capillarity test

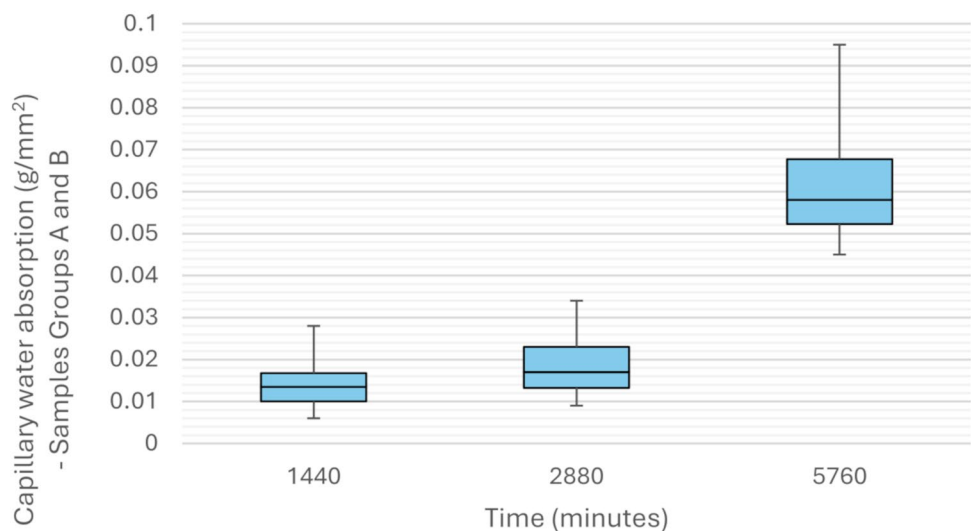


Fig. 6 Group C samples' behaviour during water absorption by capillarity test

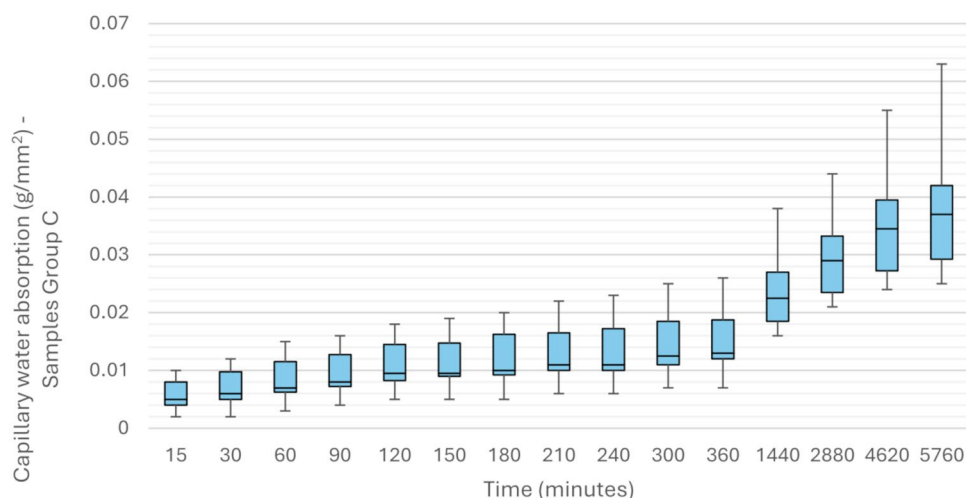


Table 2 Linear Retraction percentage values per diameter and length

ID	Diameter RETRACTION (%)	Length RETRACTION (%)
A1-1	-6,28%	1,31%
A1-2	19,30%	0,38%
A1-3	5,25%	0,28%
A1-4	1,31%	0,86%
A1-5	7,68%	0,45%
A1-6	-2,80%	0,44%
A2-1	5,23%	0,26%
A2-2	2,98%	0,69%
A2-3	3,97%	-0,26%
A2-4	3,20%	0,17%
A2-5	4,29%	0,04%
A2-6	6,16%	0,28%
Average group A1	4,08%	0,62%
Average group A2	4,31%	0,20%

negative values, probably due to the high moisture content caused by a shorter drying period, which influenced the final average. As mentioned, some samples might present negative or unrealistic values due to delamination that occurs during oven-drying process.

Although scanning electron microscopy (SEM) could provide additional microstructural evidence of delamination, it was not performed in this study due to the unavailability of SEM equipment. Instead, delamination and linear retraction were assessed through detailed visual inspection and dimensional analysis, which allowed for consistent evaluation of surface and structural changes.

The formula described in Sect. 2.3 was applied to calculate the linear retraction percentages, showed in Table 2.

These measurements provided insight into the dimensional behaviour of the material under various moisture conditions, further demonstrating its stability, as no significant dimensional changes were observed apart from the initial outer layer expansion during the drying process.

Overall, the findings indicate that the material maintains stable physical properties, which is crucial when assessing its potential for building applications where minimal dimensional alteration enhances performance.

ATR-FTIR

The results generally showed two prominent peaks between the wavelengths of 2800 and 3000 cm^{-1} , which can be associated with the C-H functional group—carbon-hydrogen bonds—typically found in alkanes. These peaks, commonly observed between 2850 and 3000 cm^{-1} , are indicative of hydrocarbons, confirming the organic nature of the material, as expected for plant samples.

In terms of specific components, measurements of the interior of the stem showed a strong correlation with powdered cellulose, indicating the presence of this polymer in the core and confirming its fibrous structure. Conversely, the outer layers of the stem were more closely correlated with carnauba (*Copernicia prunifera*) wax, a natural wax often found in plant cuticles. Additionally,

in one sample taken from the node region of the stem, the spectra were more closely associated with candelilla wax, highlighting the variation in surface composition depending on the stem location.

These findings highlight the structural complexity of the *Cortaderia selloana* stems, with the inner layers being primarily cellulose-based and the outer layers being waxy, providing insights into the material's potential performance in various applications. Figure 7 shows the results obtained.

The infrared spectra of the *Cortaderia selloana* stem interior, from analysed samples, reveal consistent and significant insights into the material's chemical composition, highlighting its fibrous and organic nature.

A broad peak around $3292\text{--}3298\text{ cm}^{-1}$ indicates the presence of hydroxyl groups (O-H), confirming the dominance of cellulose within the inner structure of the stem. This peak is typical of cellulose and hemicellulose, reinforcing the fibrous makeup of the samples. Additionally, the prominent absorption bands between 2800 cm^{-1} and 3000 cm^{-1} , attributed to C-H stretching, are indicative of hydrocarbons or alkanes, commonly found in plant-based materials, further supporting the organic nature of the *Cortaderia selloana*.

A peak at 1732 cm^{-1} is associated with C=O stretching in carbonyl groups, which are often found in lignin, esters, or carboxylic acids. This suggests the presence of lignin-like substances or possibly waxy compounds in the interior structure. Furthermore, the strong C-O stretching peak at 1031.92 cm^{-1} highlights the presence of glycosidic bonds, characteristic of cellulose and hemicellulose, further confirming the fibrous and structural role of these polysaccharides within the stem.

The more prominent peaks between 2800 cm^{-1} and 3000 cm^{-1} , in outer layer measurements, are indicative of C-H stretching vibrations, which are also associated with

waxy substances. The high concentration of waxes on the exterior surface enhances the hydrophobic properties of the stems, acting as a protective barrier that not only shields the plant from external stressors but also aids in reducing water permeability.

Overall, the combined analysis of these spectra suggests that the interior of the *Cortaderia selloana* stem is predominantly composed of cellulose, with minor contributions from lignin and hydrocarbons. This fibrous and organic composition underscores the stem's strong structural properties, balancing strength and flexibility, which could have significant implications for its potential applications in various fields, particularly in materials requiring durability and insulation.

Optical Microscopy Observations

The microscopy observations revealed significant structural differences between the outer and inner layers of the *Cortaderia selloana* stem. The outer layer, characterized by its smooth and glossy appearance, showed a dense and compact structure, suggesting a protective function. The node region, known for its density, exhibited a tightly packed arrangement of fibres, reinforcing the stem at these critical junctures.

In contrast, the interior of the stem displayed a looser, more porous structure. This soft, fibrous material appeared to contain numerous air pockets, which may contribute to the stem's thermal insulation properties. The internal fibres were less densely arranged compared to the node, but they maintained enough structural integrity to provide mechanical support.

These observations suggest that each part of the stem is specialized for different functional roles, with the outer layer providing protection, the node offering reinforcement, and the interior supporting the overall structure

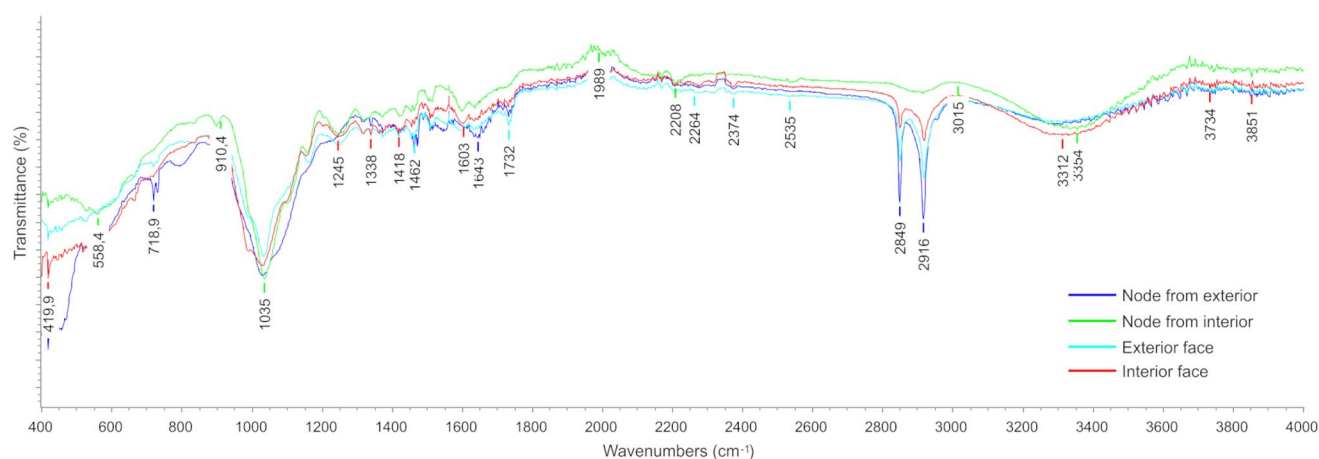


Fig. 7 ATR-FTIR Spectra

while allowing for potential applications in insulation due to its porous nature.

Figure 8 shows observations from various regions of the stem.

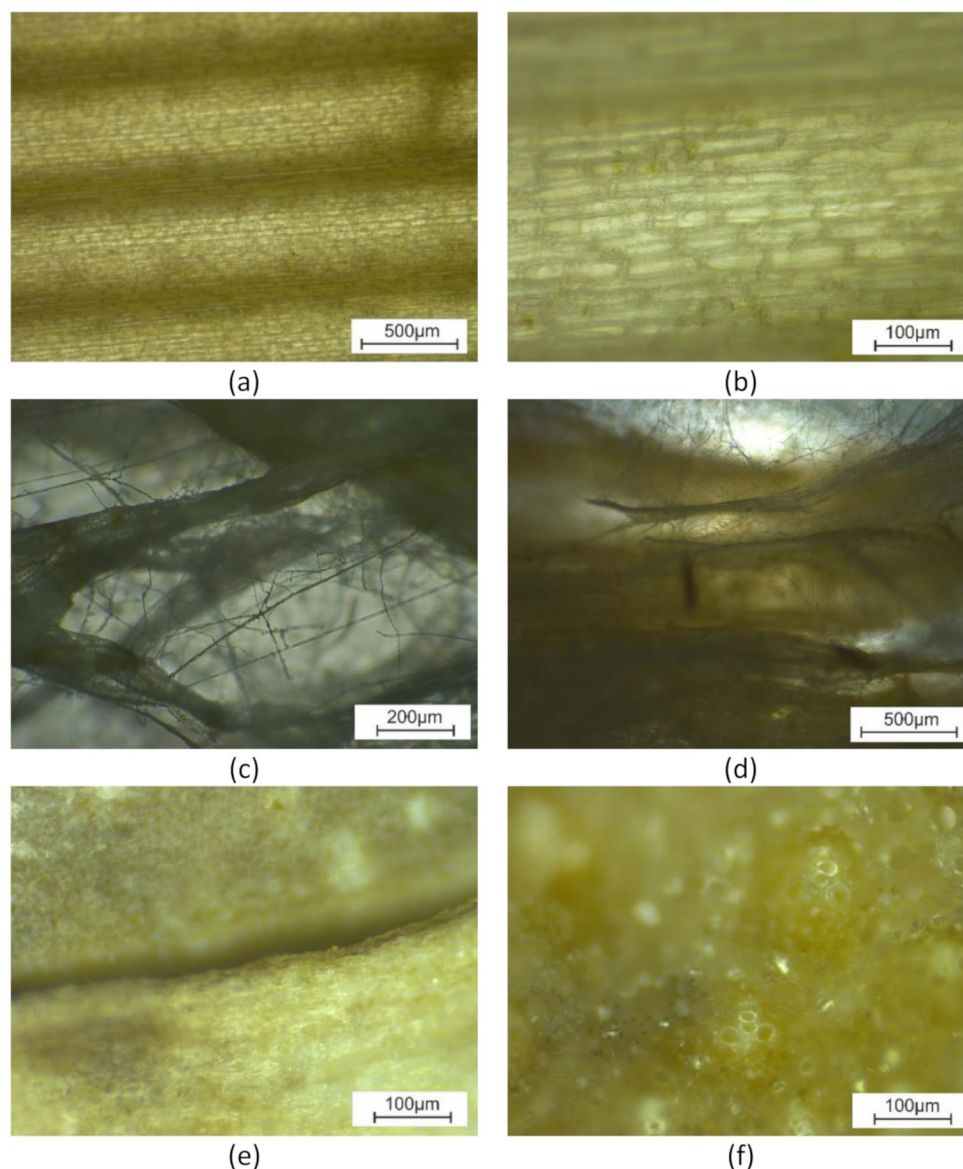
Water Contact Angle (WCA) Measurement

The results revealed distinct differences in wettability between the various stem regions. The outer layer of the *Cortaderia selloana* stem displayed hydrophilic behaviour, with a variation between almost 90° and 0° , denoting the hydrophilic behaviour. Initially, the outer surface exhibited hydrophobic characteristics, with the contact angle remaining high in the first few seconds. After approximately 20 s, the droplet's angle gradually

decreased as the surface began to absorb part of the water, indicating a transition toward hydrophilic behaviour.

Longitudinal cuts were made to assess the interior of the stem, which showed clear hydrophilic properties, reaching 0° on the node area. Water contact angles in the inner face region were measured at approximately 60° reflecting a higher level of water absorption compared to the exterior. In contrast, the denser internal region at the node displayed super hydrophilic behaviour, absorbing water almost instantly. These findings suggest that while the outer layer may resist water penetration initially, the inner structure, particularly the node, is highly absorbent, which may influence the material's overall performance in moisture-sensitive applications. Figure 9; Table 3 present the water contact angle test corresponding results.

Fig. 8 Optical microscopy images of *Cortaderia selloana* stem cross-sections showing representative microstructural features. (a) External wall region. (b) Detailed structure of the external wall. (c) Interior fibrous region. (d) Detailed view of the interior fibrous structure. (e) Node region. (f) Interior section near the node



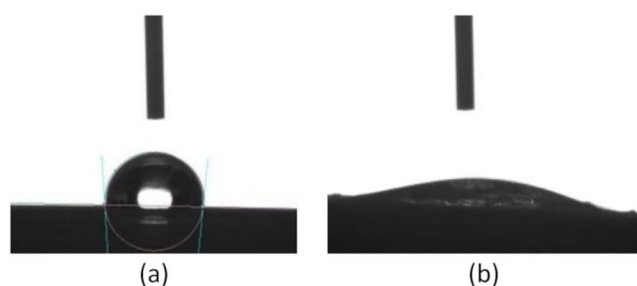


Fig. 9 Water contact angle measurement images. (a) Outer surface. (b) Inner surface

Table 3 Water contact angle measurements summary

	WCA mean	Standard deviation (S.D.)
Outer face	79,7°	1,36
Outer face on node	86,9°	5,19
Inner face	59,3°	0,75
Inner face on node	0°	----

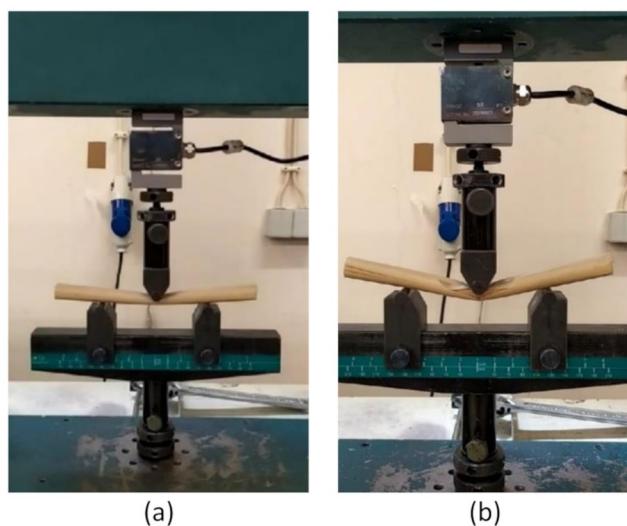


Fig. 10 Flexural strength test. (a) test setup with the sample. (b) sample at maximum flexure

Mechanical Strength

The mechanical testing revealed notable differences in the strength properties of *Cortaderia selloana* stems, depending on the region examined. Preliminary tests indicated that a more specialised testing apparatus may be required to accurately assess this type of material. However, some conclusions can still be drawn. In the flexural tests, the outer layers, particularly those near the nodes, demonstrated higher bending strength, resisting deformation without complete fracture. The core structure remained intact while the outer layers ruptured, allowing the stem to return to its original shape after the test. Figure 10 illustrates the test procedure.

In contrast, the tensile tests, where two grips held the sample ends, revealed consistent rupture points near the grips, likely due to the localized compression of fibres. The samples broke quickly after the application of tensile force, as shown in Fig. 11. These tests highlighted the mechanical superiority of the outer layers, particularly in the node areas, which displayed greater tensile strength and less elongation before rupture compared to the softer, more porous inner sections. The inner parts exhibited greater elongation but lower overall tensile strength, suggesting a role in providing flexibility rather than structural support.

A total of six specimens were tested for flexural strength and six for tensile strength. It is noted that all the tensile specimens failed near the clamping jaws, which has affected the validation of the test. Therefore, the tensile strength results are invalid and not presented. For clarity, the resulting data is summarised in Table 4.

Overall, the findings demonstrate a notable resistance to flexural deformation, notwithstanding a coefficient of variation of 39%, which underscores the inherent heterogeneity of the culm sections.

Thermal Analysis

For the thermal analysis, three samples were made using entire *Cortaderia selloana* stems, each with dimensions of 15 × 15 × 10 cm and containing approximately 120 stem units (Fig. 12).

The density table was created to verify that all *Cortaderia selloana* samples exhibited approximately the same density in terms of weight and volume. Although the samples contain voids inherent to the species' stem and the manufacturing process, they were treated as solid materials for this analysis. This information is summarised in Table 5.

The analysis was conducted in a hotbox, as detailed in Sect. 2.8. The samples were placed inside the hotbox, and any potential openings were sealed with polyurethane foam and silicone to prevent heat loss. To accommodate the irregular surfaces of the samples, an MDF closure was used to ensure proper sensor placement. The test was carried out until steady-state conditions were achieved. It is important to note that the thermal resistance value of the MDF closure, measured prior to the analysis, was excluded from the final results. The final setup for the test is shown in Fig. 13.

The results of the thermal analysis are presented in Table 6, showcasing the thermal resistance (R-value) and thermal conductivity (λ) of the *Cortaderia selloana* samples. The findings indicate that the samples possess significant insulating properties, with sample B01 exhibiting

Fig. 11 Tensile strength test. (a) sample during the test procedure. (b) sample ruptured after the test

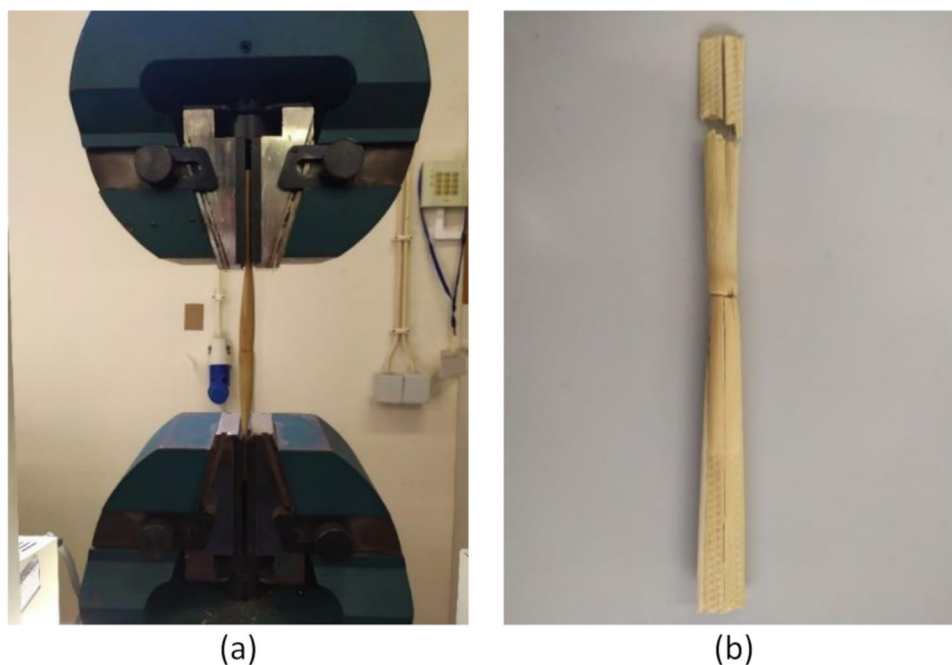


Table 4 Resulting data for flexural and tensile strength

Sample	Flexural strength (MPa)
1	7.15
2	4.14
3	3.84
4	6.58
5	10.83
6	8.58
Mean	6.85
S.D.	2.66
C.V.	39%

a thermal resistance of $2,26 \text{ m}^2\cdot\text{K}/\text{W}$ and a thermal conductivity of $0,044 \text{ W}/\text{K}\cdot\text{m}$. Sample B02 demonstrated a higher thermal resistance of $2,39 \text{ m}^2\cdot\text{K}/\text{W}$, and a lower

Table 5 Approximate density of samples

Sample ID	Weight (kg)	Volume (m3)	Density (Kg/m3)
B01	0.293517	0.00225	130.45
B02	0.29067	0.00225	129.19
B03	0.29077	0.00225	129.23
Average			129.62

thermal conductivity of $0,042 \text{ W}/\text{K}\cdot\text{m}$. In contrast, sample B03 displayed a thermal resistance of $2,17 \text{ m}^2\cdot\text{K}/\text{W}$ with a thermal conductivity of $0,046 \text{ W}/\text{K}\cdot\text{m}$.

The thermal conductivity values of *Cortaderia selloana* are comparable to those of commercially available insulation materials, such as insulation corkboard panels (ICB), which typically have thermal conductivity values around $0,04 \text{ W}/\text{K}\cdot\text{m}$. These findings indicate that

Fig. 12 *Cortaderia Selloana* insulation panel with entire stems



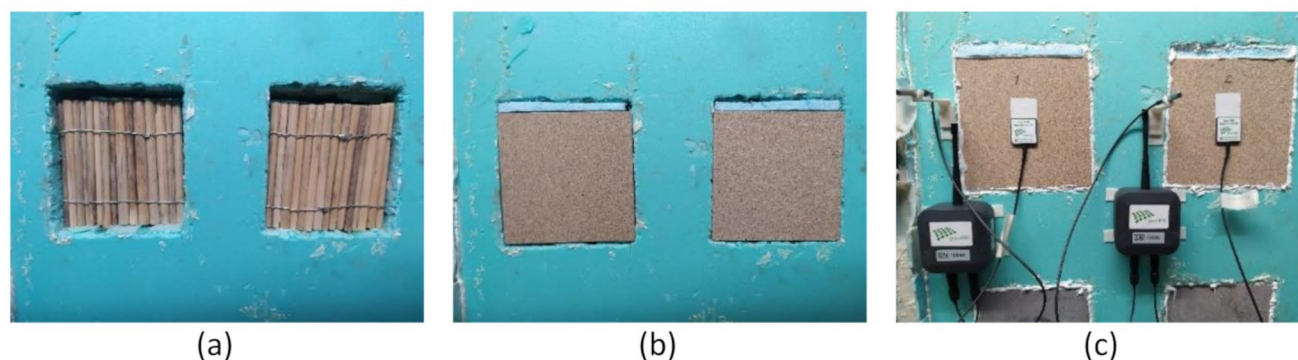


Fig. 13 Setup for the thermal test with *Cortaderia Selloana* panel samples. **(a)** Samples preparation. **(b)** MDF closure of the samples. **(c)** final setup before the test starts

Table 6 Approximate density of samples

	Thermal resistance (R -value) ($\text{m}^2 \cdot \text{K}/\text{W}$)	Thermal conductivity (λ) ($\text{W}/\text{K} \cdot \text{m}$)
B01	2,26	0,044
B02	2,39	0,042
B03	2,17	0,046

Cortaderia selloana possesses advantageous thermal properties, suggesting its potential as an effective insulating material for buildings. The minimal variation in thermal resistance and conductivity across the samples underscores the material's consistency and reliability for insulation applications, despite its heterogeneous nature.

Discussion

The characterisation of *Cortaderia selloana*'s stems reveals several promising features, particularly regarding its physical and chemical properties, which suggest significant potential for use in construction and insulation applications.

Water absorption tests revealed that *Cortaderia selloana* absorbs moisture at a controlled rate, particularly during the initial exposure. In the first 48 h, absorption increased but then stabilised, indicating that the material reached a saturation point and limited further water uptake. This behaviour reduces the risk of continuous water absorption and potential damage. The results from the control group confirm that most water absorption occurs in the early stages, after which the rate slows significantly, showing a gradual stabilisation.

Regarding the linear retraction test observations, during the drying process, an initial expansion of the outer layers was observed, which differs from conventional materials that typically shrink when moisture is lost. This expansion, followed by a return to near-original dimensions upon saturation, indicates some dimensional stability.

Despite invalid results on the mechanical test analysis, the flexural tests demonstrated strong mechanical performance, although other, more appropriate standards for thermal insulation materials can be used for more comprehensive results in future work. Even after minor ruptures in the outer layers, the core structure remained intact, highlighting the balance between flexibility and strength, which is important for materials exposed to varying mechanical stresses.

Chemical analysis through FTIR spectroscopy confirmed the fibrous and organic nature of the material. The dominant peaks corresponding to cellulose indicate that the interior structure is rich in polysaccharides, which, along with other components like hemicellulose and lignin, contribute to the material's mechanical strength. In contrast, the outer layers were found to contain waxy substances like carnauba and candelilla wax, contributing to water resistance. This combination of a fibrous core and a protective outer layer highlights the material's ability to serve structural and protective roles, making it a suitable candidate for various applications requiring durability and moisture resistance.

Although the present work focused on untreated culm biomass, it is recognised that factors such as pH, temperature, and pretreatment can significantly influence the physical and chemical properties of lignocellulosic materials. Future studies should examine how these parameters affect the structural integrity and thermal performance of *Cortaderia selloana* biomass to further optimise its use as a natural insulation material.

Microscopy observations further supported the findings, revealing a dense outer layer and a looser, porous interior. The outer layer's compactness reinforces the

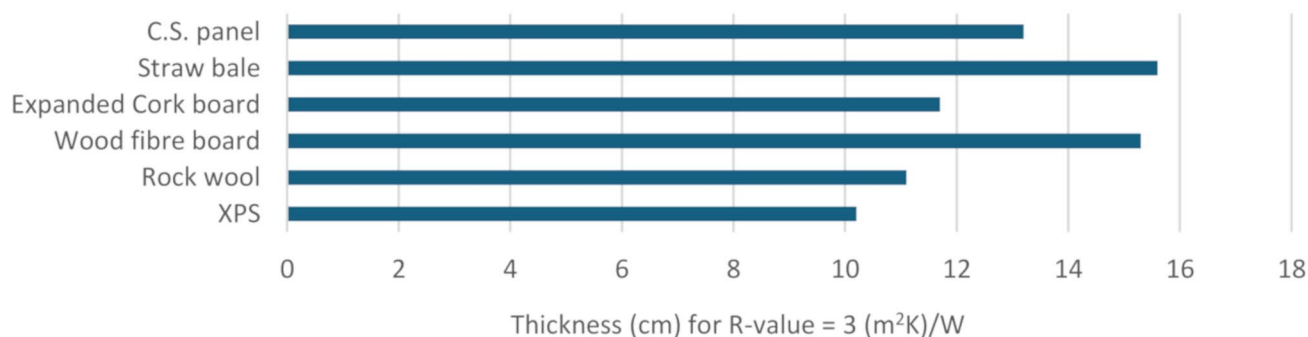


Fig. 14 Comparison of insulation materials' thickness for a thermal resistance of 3 ($\text{m}^2\text{K}/\text{W}$)

stem at critical points like the nodes, while the porous inner structure, filled with air pockets, suggests excellent thermal insulation properties. This structural complexity aligns with the thermal analysis, where the thermal resistance, along with low thermal conductivity values, demonstrates the material's capacity to act as insulation, as values are similar to commercialised bio-based insulation solutions, namely expanded cork and wood fibre insulation. Based on the measured thermal conductivity values, *Cortaderia selloana* stems could be directly used as a natural insulating material in building walls and potentially in roofing applications. Figure 14 illustrates a comparison of several materials' thickness and the proposed *Cortaderia Selloana* (C.S.) panel for the same thermal resistance of 3 ($\text{m}^2\text{K}/\text{W}$).

For every 1 cm of insulation with XPS, a conventional material with a thermal conductivity of 0.035 $\text{W}/\text{K}\cdot\text{m}$, only 1.26 cm of a panel made with *Cortaderia Selloana* stems is required. Their structure suggests they may also perform effectively in thatched roofs, as the species commonly used for traditional thatching exhibits similar morphological characteristics.

Conclusions

The results of this study demonstrate the potential of *Cortaderia selloana* as a sustainable material for use in construction, particularly as thermal insulation.

The main conclusions of this work are:

- *Cortaderia Selloana*'s stems presented an average moisture content of 9.24%. Tests also highlighted the importance of an adequate drying process, as the material holds natural moisture for a long period after harvest.
- The stems absorb moisture at a controlled rate, intensified during the first 48 h, then they show a gradual stabilisation.

- Microscopy observations revealed the porous interior structure, which is essential to understand behaviour and predict future performance of the material with different binders for panel manufacture.
- Mechanical test analysis exhibited flexibility, as the stems returned to their original form on the flexural test.
- The panel samples, with 10 cm thickness, exhibited thermal resistance values between 2.17 and 2.39 $\text{m}^2\cdot\text{K}/\text{W}$, and thermal conductivity values between 0.042 and 0.046 $\text{W}/\text{K}\cdot\text{m}$.

Future work should focus on exploring its full potential as a construction material. Additional research is needed to investigate its acoustic properties, fire resistance, and resistance to microorganisms, which are critical factors for the long-term durability and safety of building materials. Furthermore, the plant's potential as a base for biopolymers or as reinforcement for existing materials offers possibilities for its integration into broader sustainable construction practices.

The results support the need for further research to optimise its properties, exploring potential applications in various sectors and advancing the development of sustainable materials. Furthermore, the findings underscore the significance of investigating invasive species and other plants with analogous cellular structures as promising low-carbon materials to enhance the thermal performance of buildings.

Author Contributions All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Livia Cosentino. The first draft of the manuscript was written by Livia Cosentino. Diana P. Ferreira, Jorge Fernandes, and Ricardo Mateus contributed to validation, supervision, and manuscript review and editing. Diana P. Ferreira and Ricardo Mateus also provided key resources, and Jorge Fernandes and Ricardo Mateus oversaw project administration. Funding acquisition, methodology development, and visualization were led by Livia Cosentino. All authors read and approved the final manuscript.

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Data Availability The datasets generated during and/or analysed during the current study are not publicly available as they were not deposited in a repository, but are available from the corresponding author on reasonable request.

Declarations

Competing Interests The authors have no relevant financial or non-financial interests to disclose.

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