Development and Thermal Performance Assessment of Bio-Based Insulation Panels from Fountain Grass for Green Buildings

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Abstract. The growing demand for sustainable thermal insulation materials has intensified research into underutilized plant biomass with low environmental impact. This study explores the potential of Cenchrus setaceus (Forssk.) Morrone—commonly known as Fountain Grass—inflorescences as a lightweight, bio-based insulation material. T The flowers were collected after removing the stems, keeping only the floral parts, and mixed with an adhesive derived from recycled expanded polystyrene (EPS) dissolved in a diluent solution. The resulting composites were formed into panels and tested for their thermal properties. Thermal conductivity and diffusivity were determined using two complementary techniques—the Hot Disk and Box methods—yielding consistent results across both approaches. The panels exhibited a thermal conductivity of approximately 0.11 $W \cdot m^{-1} \cdot K^{-1}$ and a thermal diffusivity of 0.48 $mm^2 \cdot s^{-1}$, confirming their suitability for insulation applications. These results demonstrate that Fountain Grass inflorescences, when bound with an EPS-based adhesive, offer a dual environmental benefit: valorization of invasive plant biomass and recycling of post-consumer plastics. This synergy aligns with circular economy principles and presents a viable pathway toward eco-friendly, low-density insulation materials for green building applications.

Keywords: Bio-based insulation, Cenchrus setaceus, thermal properties, natural fibers, EPS-based binder, sustainable construction.

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1 Introduction

The building sector is one of the largest contributors to global energy consumption, particularly in hot climates where cooling demands are substantial. Enhancing the thermal performance of building envelopes is therefore a key strategy for reducing energy use and improving indoor comfort. In this context, bio-based insulation materials have emerged as a sustainable alternative to conventional synthetic insulators.

The advantages of bio-based insulation extend beyond their reduced environmental footprint; they also offer favorable thermal and hygrothermal regulation, renewability, and biodegradability. Recent studies have underscored the potential of plant fibers and agricultural residues to serve as effective insulating materials. For example, hemp fibers treated with phytic acid and urea exhibited enhanced fire resistance without compromising thermal performance, particularly when applied via a scalable spraying method [1]. Likewise, particleboards made from bean straw and rubberwood bonded with polyurethane achieved low thermal conductivity (below 0.1 $W \cdot m^{-1} \cdot K^{-1}$) and improved moisture resistance, providing a formaldehyde-free alternative to conventional boards [2].

Other bio-based solutions have demonstrated strong performance across multiple functional criteria [3,4]. Flax and hemp wools have been investigated for acoustic and hygrothermal behavior, with fiber geometry effects modeled using a composite Tarnow approach [5]. Bamboo fiberboards bonded with bone glue and sodium lignosulfonate exhibited high moisture buffering capacity (MBV = 2.5–3.9 g/$(m^2 \cdot \%RH)$) and stable thermal conductivity [4,5] while date palm fiber–starch composites achieved thermal performance suitable for hot climates [8].Corn husk fibers have also shown low effective thermal conductivities (0.038–0.042 $W \cdot m^{-1} \cdot K^{-1}$) that remain stable under varying moisture contents [9].

To contextualize recent developments, a keyword co-occurrence analysis was conducted using VOSviewer (Fig.1). A total of 159 articles published between 2020 and 2025 were retrieved from the Scopus database using the search terms “insulation + natural fibers + thermal properties + building and construction.” After removing duplicates and irrelevant entries, 104 documents were retained for analysis. Keywords with at least five occurrences were clustered to reveal thematic research domains. As shown in Figure 1, most studies concentrate on thermal properties—particularly thermal conductivity—alongside hygroscopic and mechanical behavior. A smaller yet significant portion of research focuses on mechanical enhancements such as improved flexural strength, linking these properties to potential gains in building energy efficiency. This reflects the growing recognition of plant-based fibers as viable candidates for eco-friendly insulation, combining low thermal conductivity with abundance, biodegradability, and minimal environmental impact.

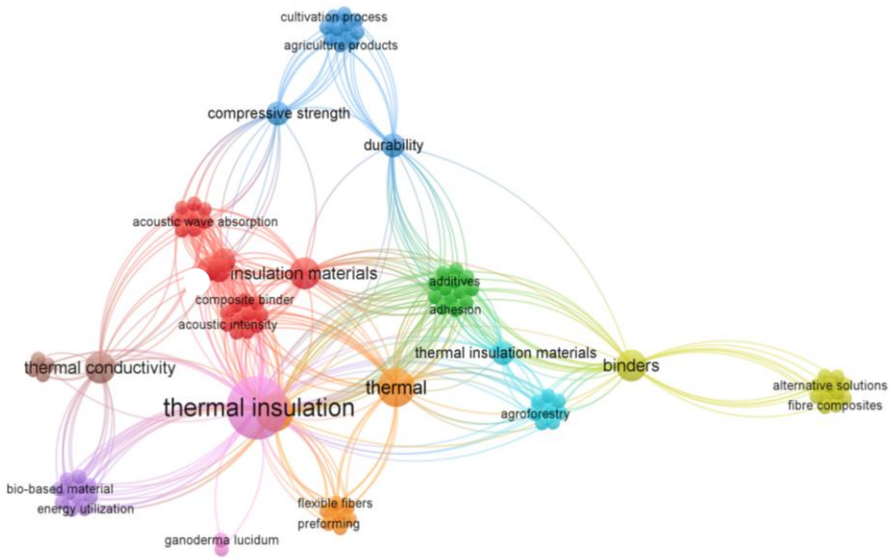

Fig. 1. Thermal Insulation Materials for Green Buildings: Insights from a Keyword Network Analysis.

Fountain Grass (*Cenchrus setaceus*) is widely recognized as an invasive perennial, found in over 25 countries and producing abundant biomass, especially in arid and semi-arid climates. In regions such as Australia's Northern Territory and South Australia, infestations cover tens of thousands of hectares. Similar widespread presence is observed across North Africa and the Arabian Peninsula, where the species colonizes disturbed lands and roadsides. Yields from regional studies are significant, typically ranging from 8 to 12 tons of dry biomass per hectare annually. This level of natural availability makes Fountain Grass a promising and sustainable feedstock for bio-based insulation, supporting both resource recovery and ecological restoration by turning invasive growth into valuable building materials [10].
Building on this growing body of work, the present study investigates an innovative insulation panel fabricated from the inflorescences of Cenchrus setaceus (Fountain Grass), a fast-growing and drought-tolerant species. The floral fibers are combined with a diluted adhesive derived from recycled expanded polystyrene (EPS), thereby valorizing two underutilized waste streams. By leveraging low-cost raw materials and energy-efficient processing, the study aims to develop an environmentally responsible and thermally efficient insulation solution tailored to hot and arid climates. Thermal performance is assessed using two complementary techniques—the Hot Disk method and the Box method—to ensure robust evaluation and comparison with conventional insulating materials.

2 Methodology

2.1 Sample Preparation

Cenchrus setaceus (Forssk.) Morrone, abbreviated as CsFM, was selected as the bio-based reinforcement for this study. The specimens were manually harvested from unmanaged arid zones during the flowering stage. To ensure consistency, only the floral components were retained, with stems and leaves carefully removed. The collected material was air-dried under natural conditions for several days to reduce its moisture content.

Two composite formulations were prepared with fiber-to-binder weight ratios of 70/30 and 90/10, respectively. The dried CsFM inflorescences were manually mixed with a polystyrene-based adhesive, prepared by dissolving post-consumer expanded polystyrene (EPS) waste in a cellulosic diluent (commercial formulation used for paint and polymer dissolution). This solvent was selected for its ability to partially depolymerize EPS and promote uniform dispersion within the composite matrix.
The mixtures were shaped into geometries tailored to the testing methods. For the Box Method, samples were molded into rectangular panels measuring 27 × 27 × 3 cm³ (length × width × thickness). For the Hot Disk Method, cylindrical specimens with a 10 cm diameter and 3 cm thickness were fabricated according to Transient Plane Source (TPS) requirements. All samples were cured under ambient conditions until the adhesive fully hardened, ensuring dimensional stability and structural integrity.

Fig. 2. Main stages in the manufacturing process of the insulation boards.

The structural composition of CsFM fibers was first examined using X-ray diffraction (XRD). As illustrated in Fig. 3 (right), the diffraction peaks at 2θ = 17°, 22°, and 35° confirm the presence of cellulose I crystalline phases, characteristic of lignocellulosic fibers commonly employed in thermal insulation materials [11,12].

2.2 Hot Disk Method

Thermal characterization of the composites was then conducted with the Hot Disk method, based on the Transient Plane Source (TPS) technique. This method allows simultaneous measurement of thermal conductivity (λ), thermal diffusivity (α), and volumetric heat capacity (Cv), with advantages of rapid testing and flexible sensor design. In this study, experiments were performed using the Hot Disk TPS 2200 system (Hot Disk, Sweden), following ISO 22007-2:2015. A symmetric double-sample configuration was adopted, with a Kapton sensor positioned between two identical cylindrical specimens. During testing, a constant electrical power of 20–40 mW was applied for 160–320 s, generating a transient thermal response. The temperature data were recorded and analyzed with Hot Disk thermal analyzer software (v7.3) to extract the thermal parameters accurately.

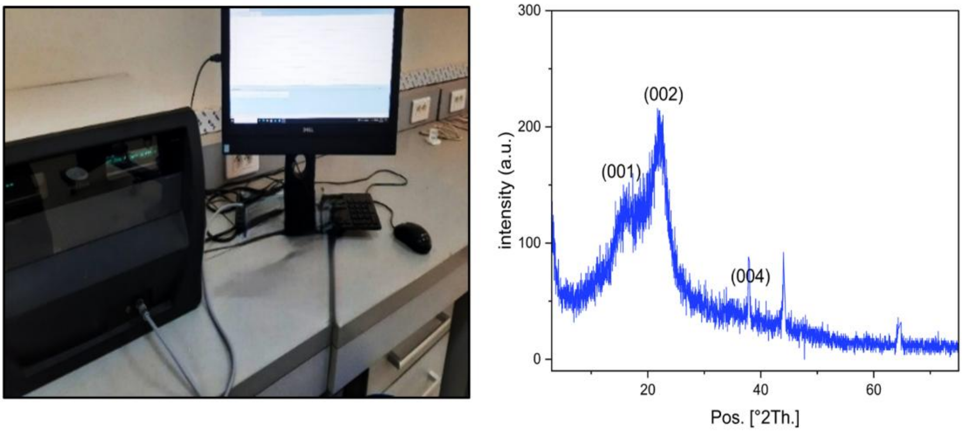

Fig .3. (left) Hot Disk setup, (right) XRD diffractograms of CsFM fibers.

2.3 Box Method

The Box Method was used to measure thermal conductivity under controlled steady-state conditions. Rectangular specimens (27 × 27 cm², 3–7 cm thick) were positioned between a heated upper plate and a cooled lower plate (glycol–water mixture at –5 °C). The upper plate was heated with an electrical resistor delivering a uniform heat flux (U^2/R).
After 2–3 hours, steady-state conditions were reached and thermal conductivity (λ) was calculated using the expression adapted from Mustapha et al. (2014):

$$\lambda = \frac{e}{S(T_C - T_F)}\left[\frac{U^2}{R} - C(T_B - T_{amb})\right] \quad (1)$$

Where:
λ: thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
e: specimen thickness (m)
S: specimen surface area (m²)
U^2/R: electrical power delivered to the heater (W)
C: overall heat-loss coefficient from box to room ($W \cdot °C^{-1}$)
T_C, T_F: hot and cold surface temperatures at the specimen interfaces (°C)
T_B: box interior air temperature (°C)
T_{amb}: room ambient temperature (°C)
To optimize measurement precision, the temperature difference between the box interior and the ambient environment was maintained below 1 °C by regulating heating power

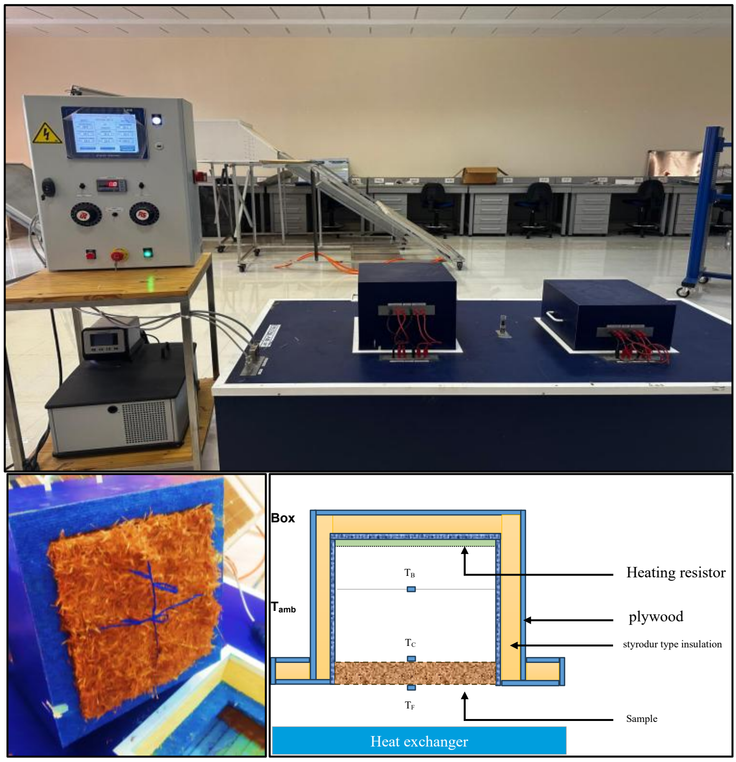

Fig.4. Schematic of the Box Method for determining thermal conductivity.

2.4 Dynamic Heat-Transfer Simulation of Insulated Wall

A multilayer wall system was modeled using ANSYS Fluent to evaluate the dynamic thermal performance of CsFM-based insulation panels. The wall configuration consisted of: (i) external cement plaster, (ii) perforated brick layer, (iii) an air cavity either uninsulated or filled with 2, 4, or 6 cm of insulation, (iv) a second perforated brick layer, and (v) internal cement plaster.

The simulation used real summer climate data from Oujda, Morocco (July 10, 2023), with outdoor air temperatures ranging from 24 °C to 46.1 °C and nighttime temperatures between 25 °C and 29 °C. These conditions were selected to test the wall's response under severe diurnal fluctuations.

Results indicated that incorporating CsFM insulation significantly reduced indoor temperature peaks and moderated daily fluctuations. Increasing insulation thickness further enhanced thermal resistance, suggesting the potential of this bio-based solution to reduce cooling loads and improve indoor comfort in hot, arid climates.

3 Results and Discussion

3.1 Thermal Properties

The thermal conductivity and diffusivity of the insulation composites were evaluated using two complementary experimental techniques: the Hot Disk (transient plane source) method and the steady-state Box Method.

The Hot Disk method yielded thermal conductivities of 0.11 $W \cdot m^{-1} \cdot K^{-1}$ for the 70/30 formulation and 0.082 $W \cdot m^{-1} \cdot K^{-1}$ for the 90/10 formulation, with corresponding thermal diffusivities of 0.43 $mm^2 \cdot s^{-1}$ and 0.37 $mm^2 \cdot s^{-1}$, respectively. These low values reflect a limited ability of the material to transfer heat, confirming its suitability for thermal insulation applications.

The Box Method provided slightly higher values: 0.12 $W \cdot m^{-1} \cdot K^{-1}$ for the 70/30 formulation and 0.089 $W \cdot m^{-1} \cdot K^{-1}$ for the 90/10 formulation. The small divergence between the two techniques can be attributed to differences in experimental conditions: the Hot Disk captures localized and transient heat transfer behavior, while the Box Method characterizes global, steady-state performance, which is more sensitive to parasitic thermal losses.

In addition, density and specific heat capacity highlight both the lightweight nature and moderate thermal inertia of the composites. The measured densities were 230 $kg \cdot m^{-3}$ (70/30) and 227 $kg \cdot m^{-3}$ (90/10). Based on the measured values of thermal conductivity (λ), density (ρ), and thermal diffusivity (α), the specific heat capacity (c_{p}) was calculated using:

$$c_p = \lambda / \rho\alpha \tag{2}$$

These findings are consistent with those reported by Benallel et al. who developed insulation panels using 40% date palm waste and 60% recycled cardboard bound with water, achieving thermal conductivities in the range 0.074–0.081 $W \cdot m^{-1} \cdot K^{-1}$. Similarly, Bovo et al. reported that corn cob–based composites exhibited thermal conductivities between 0.14 and 0.26 $W \cdot m^{-1} \cdot K^{-1}$, depending on configuration. Together, these comparisons highlight that increasing fiber content generally lowers density and enhances thermal performance by reducing conductivity, albeit sometimes at the expense of specific heat capacity. In comparison, the thermal conductivity of the Fountain Grass composites (0.082–0.12 $W \cdot m^{-1} \cdot K^{-1}$) lies within the range of commercial and natural insulation materials. Conventional mineral wool and expanded polystyrene (EPS) typically exhibit conductivities of 0.035–0.040 $W \cdot m^{-1} \cdot K^{-1}$ [13], while bio-based alternatives such as hemp, flax, or straw panels range between 0.045 and 0.090 $W \cdot m^{-1} \cdot K^{-1}$, depending on density and moisture content [10,11]. Although the Fountain Grass panels show slightly higher conductivity than synthetic insulators, their performance remains comparable to other plant-based systems and suitable for low-energy buildings. Their renewable nature and the widespread availability of Cenchrus setaceus in semi-arid regions provide clear environmental advantages. This balance of insulation performance, sustainability and cost highlights the industrial relevance of Fountain Grass panels.

Beyond performance metrics, the environmental advantages of utilizing plant-based biomaterials in construction—such as renewability, biodegradability and low embodied energy—reinforce the significance of further thermo-mechanical investigations of bio-based insulation materials.

3.2 Dynamic Thermal Simulation

Figure 5 presents the simulated evolution of indoor air and inner wall surface temperatures over a 24-hour summer cycle for varying insulation thicknesses (0, 2, 4, and 6 cm) of CsFM-based panels. In the uninsulated case, the indoor air temperature peaked at approximately 29.5 °C, illustrating strong solar heat gains through the wall. The inclusion of the bio-based insulation reduced the maximum indoor temperature to 28.3 °C, 28.1 °C, and 27.7 °C for thicknesses of 2, 4, and 6 cm, respectively—representing a decrease of about 1.8 °C (≈ 6 %) compared to the uninsulated configuration.

Beyond reducing peak temperatures, the insulation significantly altered the wall's thermal dynamics. Increasing panel thickness both attenuated the amplitude of temperature fluctuations (from roughly 2.8 °C without insulation to 1.0 °C with 6 cm) and introduced a thermal lag of nearly 3 hours between outdoor and indoor temperature peaks. This combined damping and delay effect helps maintain a more stable indoor environment during peak afternoon hours, thereby improving occupant comfort and lowering cooling demand.

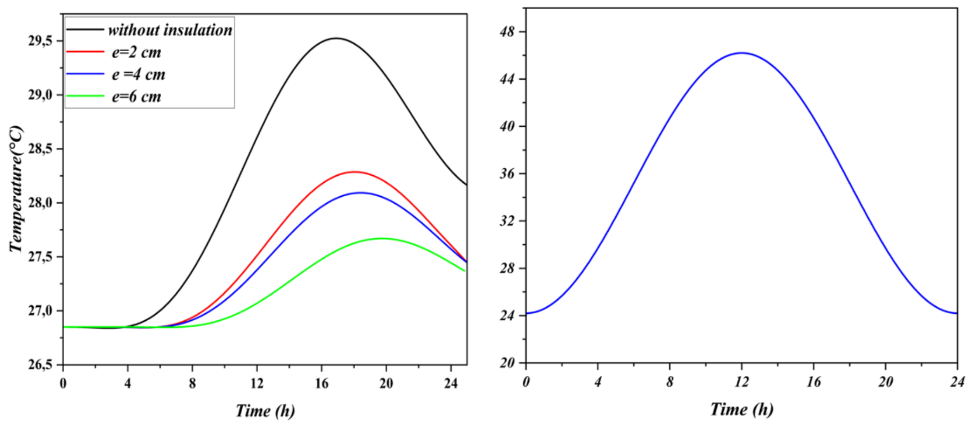

Fig. 5. Average inner surface temperature of the wall over a day for different insulation thicknesses.

Overall, these results highlight the strong potential of CsFM-based composites to enhance passive thermal performance in building envelopes, particularly in hot and arid regions where diurnal temperature variations are pronounced.

4 Conclusions

This study demonstrated the feasibility of using Cenchrus setaceus (Fountain Grass) inflorescences combined with a recycled-EPS binder to produce lightweight, bio-based insulation panels. The composites exhibited low thermal conductivities (0.082–0.12 $W \cdot m^{-1} \cdot K^{-1}$) and moderate thermal inertia, confirming their suitability for thermal insulation applications.

Dynamic simulations under Oujda's summer climate further validated their performance, showing that integrating 2–6 cm of CsFM insulation into a multilayer wall can reduce indoor temperature peaks by up to 1.8 °C and delay heat transfer by approximately 3 hours. These outcomes underscore the material's capacity to moderate indoor thermal loads and support passive cooling strategies in arid climates.

Beyond energy efficiency, this approach contributes to the circular economy by valorizing invasive plant biomass and post-consumer plastics, offering a sustainable pathway for eco-friendly construction materials. Future research will focus on mechanical durability, hygrothermal performance, and life-cycle analysis to assess the scalability of CsFM-based panels in real-world applications.

5 Reference

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