Hygrothermal Performance of Binderless Luffa Fiber Insulation Panels for Energy-Efficient Building Applications

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Abstract. The global interest in environmentally responsible building materials has accelerated the development of insulation products based on renewable bio-resources. This study examines the hygrothermal behaviour of insulation panels fabricated from luffa cylindrica materials using a wet-forming process. Three panel types were uniformly fabricated and tested for thermal and moisture responses. Steady-state thermal resistance was evaluated at mean temperatures between 10 and 40 °C using a heat-flow-meter apparatus. All samples exhibited a linear decrease in thermal resistance with increasing temperature, reflecting the enhanced heat transfer mechanisms within the interconnected porous network. Among the panels, the specimen with the most homogeneous void structure demonstrated the highest thermal performance. Moisture uptake was analysed under controlled relative humidity levels generated by using saturated salt solutions. The samples displayed typical Fickian absorption behaviour, with equilibrium moisture contents (EMC) increasing predictably with relative humidity but remaining largely unaffected by differences in panel thickness. The EMC values converged at approximately 10, 13, and 16% for the three humidity conditions of 54, 75, and 95%, respectively. The findings reaffirm the potential of luffa-based binderless composites as lightweight bio-insulation for sustainable building applications, offering stable hygrothermal properties and reduced environmental impact.

1 Introduction

The development of bio-based insulation materials derived from agricultural residues and naturally occurring fibrous plants has gained increasing attention as sustainable alternatives to conventional building-insulated envelopes. Binderless lignocellulosic composites offer notable advantages, such as low-cost, lightweight, biodegradable, and can be produced with minimal energy input due to the inherent self-bonding ability of cellulose, hemicellulose, and lignin components [1-2]. These attributes make them especially attractive for use in low-

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carbon building applications where thermal, acoustic, and hygroscopic performance directly influence indoor comfort and operational energy demand. Numerous studies have demonstrated that natural fibers such as bagasse, kenaf, bamboo, wheat straw, and wood residues can be converted into functional insulation panels without the addition of synthetic binders, thereby eliminating the environmental and health concerns associated with volatile organic compound (VOC) emissions commonly found in resin-based products [3-7]. Despite these advantages, bio-based fibers also exhibit limitations, for instance, they are hygroscopicity, dimensional instability, and performance sensitivity to moisture, requiring targeted investigation to optimize their use in practical construction settings [8].

The thermal performance of lignocellulosic insulation depends strongly on several microstructural factors, including fiber morphology, void content, porosity, and density. Variations in these characteristics influence the balance between conductive, convective, and radiative heat transfer inside the porous matrices [9]. Previous investigations on binderless fiber composites have shown that the presence, size, and distribution of voids significantly modify thermal conductivity, particularly at elevated temperatures where air-phase conduction becomes more dominant [2],[10-11]. Likewise, the adsorbed moisture content of fibrous materials plays a crucial role in thermal transport, where water has a much higher thermal conductivity than air, and therefore rising humidity or water absorption, leading to an increase in heat transfer and a corresponding reduction in thermal resistance. Understanding the coupled heat and moisture behaviour (hygrothermal performance) of bio-based insulation materials is critically important, as buildings operate under dynamic environmental conditions where temperature and relative humidity fluctuate continuously [12-13]. Materials that can absorb moisture while retaining stable thermal performance are especially valuable for green building applications in humid climates.

The present study investigates the hygrothermal performance of binderless insulation panels manufactured from luffa cylindrica fibers, a highly porous, lightweight, and naturally sponge-like plant material that has not been extensively examined for thermal insulation applications. The main objectives are the fabrication process, determination of temperature dependence of the thermal resistance of luffa-based panels, evaluation of moisture absorption behaviour under controlled relative humidity using the desiccator method to quantify hygrosopic response and equilibrium moisture content. By integrating thermal and moisture analyses, this work aims to provide insights into the suitability of luffa-based binderless composites for energy-efficient building envelopes and sustainable construction.ture dependence of the sample and not its mechanical and any other properties.

2 Materials and Methods

Raw dry luffa sponge (*luffa cylindrica (L.) M. Roem)* was used for producing the bio-based insulation panels. They were cut into smaller species before grinding to extract the finer fiber materials. The fabrication process (see Fig. 1) of the luffa-based insulation panel was carried out using a wet-forming and drying approach according to the standard BS EN 622-4:2024. Initially, raw luffa sponges (Fig. 1a) were mechanically cleaned and processed to obtain uniform fibrous particles (Fig. 1b). These fibers were then dispersed in water to create a homogeneous slurry, enabling improved fiber distribution and enhanced bonding during forming. The slurry was subsequently transferred into a mold, where excess water was removed through filtration and gratvitional compression to achieve the desired panel thickness and density. Finally, the formed panels (Fig. 1c) were dried under controlled temperature and humidity conditions to ensure dimensional stability and to remove residual moisture without degrading the natural fibers. This integrated wet-forming and drying process yielded lightweight, binder-free insulation panels with stable structure and promising thermal performance.

Fig. 1. Fabrication process of bio-based insulation panel derived from luffa materials: raw luffa sponges (a); fine fiber particles (b); final luffa panel (c).

The thermal conductivity coefficient was measured in accordance with standard test for steady-state heat transfer by hot-flow-meter (HFM) method according to standards EN 12667:2001, and ISO 8301:1991/Amd 1:2002. Three samples at different thicknesses (10, 15, and 20 mm) were prepared for the thermal conductivity measurement. For any mean temperature tested, the temperature difference between the cold and hot sides of the specimen was set to be constant at 10 °C.

The water absorption-relative humidity relation was investigated using the desiccator method according to the standard ISO 12571:2021. Samples having the same thickness were moistened in a sealed desiccator containing saturated salt solutions which were prepared by mixing salt and distilled water. Table 1 presents the relative humidity levels selected for measuring water absorption at the room temperature and the required salt solutions.

Table 1. Standard humidity levels above saturated solutions in equilibrium state.

Salt Solution	Saturated RH (%)
Magnesium nitrate ($Mg(NO3)_2$)	54
Sodium chloride (NaCl)	75
Potassium nitrate (KNO_3)	95

3 Results

Thermal resistance values (RSI, $m^2{\cdot}K/W$) were calculated through thickness of samples and their measured thermal conductivity. All samples showed a consistent decrease when the mean temperatures increase from 10 to 40 °C as seen in Fig. 2. This behaviour aligns well with the general thermal characteristics of low-density, porous, lignocellulosic materials, in which heat stransfer through the air-filled pores becomes more pronounced at elevated temperatures [14]. Since air is the dominant heat-carrying medium in such bio-based materials, its thermal conductivity increases with temperature due to enhanced molecular mobility, leading to a proportional decrease in the overall thermal resistance of the panel. Additionally, radiative heat transfer across pore boundaries intensifies with temperature, further contributing to the reduction in resistance.

The three panels exhibit clearly distinct thermal resistance levels, reflecting differences in fiber concentration, pore distribution, void fraction, and their own compaction during fabrication. LF3 consistently demonstrates the highest thermal resistance (about 0.396 $m^2{\cdot}K/W$) across all temperatures, suggesting that this sample possesses a more effective internal microstructure, probably by a more homogeneous network of interconnected fibers and more uniformly distributed voids. This structure can suppress convective and radiative heat transfer more effectively, resulting in superior insulating capacity. In contrast, LF1 shows the lowest thermal resistance (0.194 $m^2{\cdot}K/W$) and the steepest decline with temperature. This may indicate a looser or less uniform fiber arrangement, larger voids, or increased local anisotropy in the fiber orientation. Larger or poorly distributed voids can create preferential heat pathways that accelerate conduction through the material. Such effects become more pronounced as temperature rises, amplifying differences between the samples. The identical linear decrease and high consistency of coefficient of determination (R^2) indicates that no structural degradation or phase transition occurs within this temperature range. This stability is important for practical applications, as it confirms that luffa-based insulation maintains predictable and reliable thermal behavior under normal building operating conditions. However, the downward trend highlights the importance of considering climate and placement when integrating such bio-based insulation into building envelopes. These materials perform best at lower temperatures, such as in winter conditions or in regions with mild climates, while their effectiveness gradually diminishes in hot environments due to increased conductive and radiative transfer.

Overall, the results reinforce that the microstructural attributes of binderless luffa panels, specifically the size, number, and distribution of voids play a pivotal role in determining their thermal resistance. Optimizing fiber preparation, wet-forming conditions, and drying protocols could further enhance the panels' insulation performance. These insights not only underline the potential of luffa-based materials for green building applications but also provide a foundation for tailoring bio-composites with improved hygrothermal properties.

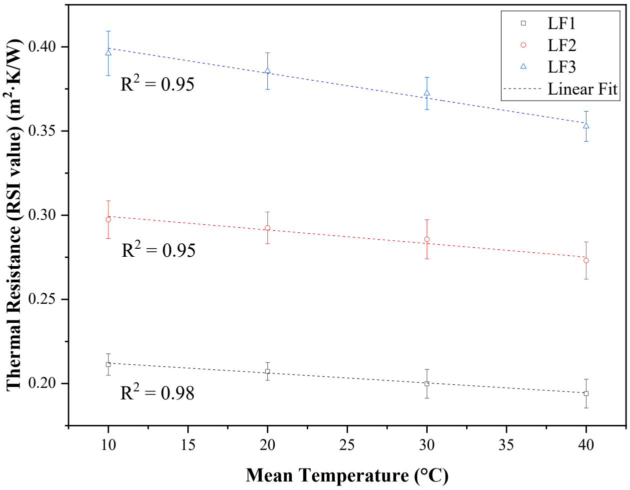

Fig. 2. Thermal resistance values and their deviation of the three-panel types as a function of mean temperature.

The hygroscopic behaviour of nine samples (derived from binderless luffa-based panels LF1, LF2, and LF3) was practical examined under controlled relative humidity (RH) environments generated by saturated salt solutions (Table 1). Water absorption percentages of the samples with thicknesses of 10, 15, and 20 mm over a 30-day exposure period in conjunction with increased humidity levels were shown in Fig. 3, reflecting the strong hygrosopic nature of lignocellulosic materials.

Across all samples, the moisture content increased systematically with increasing RH. At low level of humidity (54% RH), the samples exhibited moisture contents between 7.0 to 10.5% after 30 days. These values corresponds to monolayer adsorption and diffusion through fiber walls. At 75% RH, the absorption rate rose significantly, highlighting the progressive enhancement of sorption to hydrophilic sites in cellulose and hemicellulose within the cellulosic fibers. The last sorption recorded a highest level, ranging from 15.5 to about 16% due to the capillary condensation in large pores at high relative humidity, and the

the equilibrim state occurs when the chemical potential of water in the fiber equals that of the surrouding vapour. Results also figured out the hygrosopic behaviour of lignocellulose-based materials, contain numerous hydroxyl (−OH) groups capable of hydrogen bonding with water molecules.

Generally, the behaviour of moisture uptake demonstrate that lignocellulosic materials exhibit strong RH-dependent hygroscopicity, where higher humidity environments always lead to large absorption. In addition, it is seen from the curves that water absorption followed a Fickian diffusion process, starting with a rapid uptake due to a large number of water particles diffused greatly into the most accessible hydrophilic sites of cellulose, hemicellulose, and lignin components. This corresponds to the steep slope at the beginning of the curves, indicating hydrogen bonding with hydroxyl groups of the fibers. From 14 to 28 days, the absorption level slows down as the number of capillaries of celluosic fiber which were filled originally with air were slowly replaced by penetrated water, causing a small change in the total mass. Finally, the saturation level was obtained after 30 days. At this stage, the absorption curve flattens, showing a steady-state balance between sorption and desorption processes.

Despite substantial differences in sample thickness, the equilibrium moisture content (EMC) remained largely independent of thickness across all RH conditions. For example, at 75% RH, samples of LF2 reached 12.65%, 13.29%, and 13.02% at 10, 15, and 20 mm, respectively, showing negligible differences (< 0.3%). A similar convergence was observed at 90% RH, where all thickness groups stabilized near 15.5–16.0%. This behaviour confirms the fundamental material principle that moisture sorption is governed by the intrinsic chemical and microstructural properties of the fiber network, rather than by sample geometry. Only substantial differences in bulk density or porosity would be expected to alter the normalized moisture content, which was not observed here. However, thickness influenced the sorption kinetics, with thicker samples requiring longer exposure times to reach equilibrium due to extended diffusion pathways. This is consistent with Fickian moisture transport in porous matrices [15].

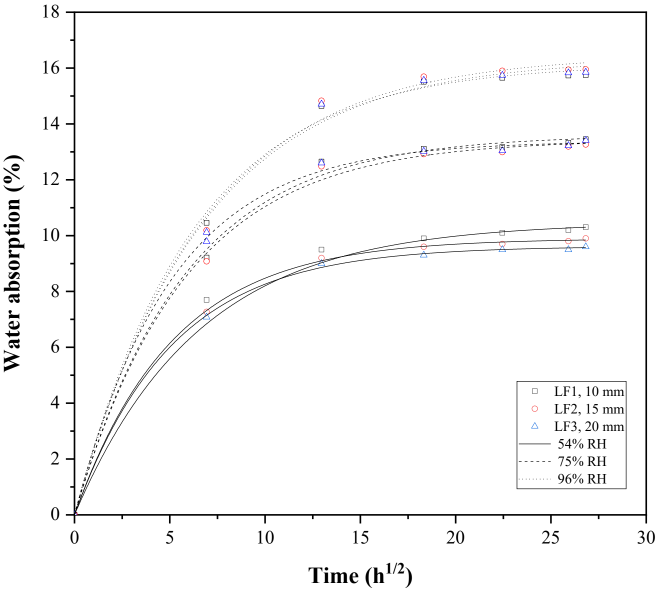

Fig. 3. Average water absorption percentages of luffa samples regarding the absorbent time moistening in three environmental humidity generated by different salt solutions.

4 Conclusions

This study provides a practical investigation of the thermal and hygroscopic behaviour of binderless luffa fiber panels for building-insulated applications. Thermal resistance measurements report a clear temperature-dependent across all samples, driven by enhanced conductive and radiative heat transfer within the air-filled porous network at higher temperatures. Among the three panel formulations, LF3 consistently delivered the highest thermal resistance because of its more favourable microstructural uniformity and optimized void distribution. The hygroscopic examination demonstrates that moisture uptake strongly depends on ambient relative humidity but is largely independent of sample's thickness. All samples exhibited classical Fickian sorption behavior with equilibrium moisture contents (EMC) converging at about 10, 13, and 16% for 54, 75, and 95% relative humidity, respectively. The similar EMC values across different thicknesses confirm that moisture sorption is governed by fiber chemistry and porosity rather than sample geometry. Overall, these findings highlight the potential of luffa fiber composites as viable bio-based materials with stable and predictable hygrothermal performance. Their temperature-dependent thermal resistance and controllable moisture sorption make them promising candidates for energy-efficient building envelopes, particularly in climates where sustainable, low-carbon materials are prioritized.

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