Effects of Mycelium-based Thermal Insulation Board Uniformity on Insulation Performance and Overall Physical Properties: Pathways for Future Quality Enhancements

Yuttana Tongtuam,[a,b,c,*,†] Praween Jinanukul,[a,d,†] Saisamorn Lumyong,[e,f] and Worawoot Aiduang[e,g,*]

* *Corresponding author: yuttana.t@cmu.ac.th; worawoot.aiduang@cmu.ac.th*

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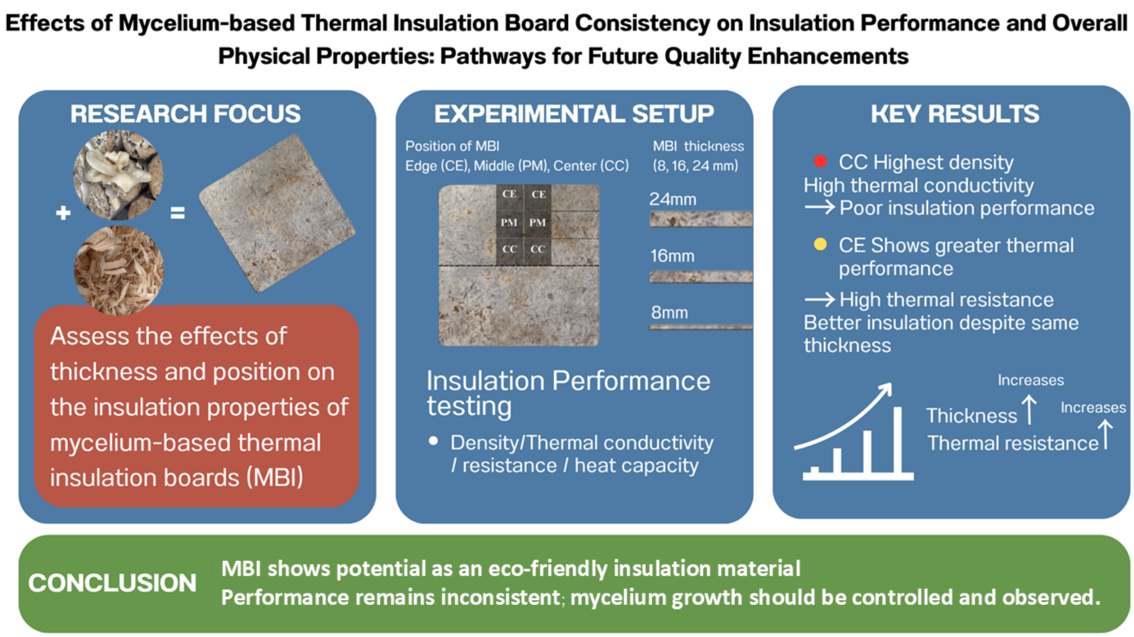
GRAPHICAL ABSTRACT



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The impact of internal uniformity was studied relative to the insulation performance and properties of mycelium-based insulation boards (MBI) made from *Lentinus sajor-caju* and corn husk. The study examined how variations of mass per unit area and board thickness affected density, thermal conductivity, thermal resistance, and heat capacity. Density gradients were observed in the boards, ranging from 157 to 181 kg/m³, highest at the centerline and lowest at the edges. Thermal conductivity increased with density (0.049 to 0.063 $W \cdot m^{-1} \cdot K^{-1}$), while thermal resistance increased from center to edge, peaking at 0.471 $m^2 \cdot K \cdot W^{-1}$ at the 24 mm edge. Heat capacity was stable across samples (0.132 to 0.143 kJ/kg·K), indicating consistent thermal energy retention. Microscopic analysis confirmed these trends, showing structural compaction at the center and greater porosity at the edges, correlating with insulation performance. Pearson correlation analysis confirmed strong relationships between density, position, and thermal properties, notably a significant negative correlation between density and distance from the edge ($r = -0.858$, $p = 0.003$ at 16 mm thickness) and a strong positive correlation between thickness and thermal resistance ($r = 0.999$, $p < 0.001$). These findings support MBI boards as eco-friendly, high-potential alternatives to traditional insulation materials, allowing for further performance enhancement through optimized growth and mold design.

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Keywords: Green composites; Mycelium technology; Insulation materials; Utilizing agricultural waste; Sustainable development goals; SDGs

Contact information: a: Faculty of Architecture, Chiang Mai University, Chiang Mai 50200, Thailand; b: Materials Science Research Center, Faculty of Science, Chiang Mai University, Chiang Mai 50200, Thailand; c: Center of Excellence in Materials Science and Technology, Chiang Mai University, Chiang Mai 50200, Thailand; d: Doctor of Philosophy Program in Architecture (International Program), Faculty of Architecture, Chiang Mai University, Chiang Mai 50200, Thailand; e: Department of Biology, Faculty of Science, Chiang Mai University, Chiang Mai 50200, Thailand; f: Center of Excellence in Microbial Diversity and Sustainable Utilization, Chiang Mai University, Chiang Mai 50200, Thailand; g: Office of Research Administration, Chiang Mai University, Chiang Mai 50200, Thailand; †These authors contributed equally to this work;

**Corresponding authors: yuttana.t@cmu.ac.th; worawoot.aiduang@cmu.ac.th*

INTRODUCTION

The widespread use of synthetic materials, such as cement, concrete, and polymers, presents significant environmental challenges due to their long disintegration times, high pollution levels, and waste creation (Muir and Howard 2006; Gagg 2014; Olivier *et al.*

2017). The manufacturing of these materials also involves complex machinery, expensive raw materials, and high energy consumption, contributing further to environmental harm (Chaturvedi *et al.* 2003; IEA 2019; Raabe 2023). In response, a global movement aligned with the United Nations Sustainable Development Goals (SDGs), specifically SDG 9 (Industry, Innovation, and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action), has been driving the shift towards more sustainable materials and technologies (United Nations 2023). This is especially crucial in the construction and building materials sector, where alternatives to conventional, pollution-heavy materials are urgently needed, particularly in the insulation industry (Dias *et al.* 2021; Neri *et al.* 2021; Rabbat *et al.* 2022).

One promising solution lies in green composite materials, which are not only efficient but also hold significant potential for replacing traditional synthetic materials. These materials, often produced from natural substrates, offer sustainability, eco-friendliness, and biodegradability, making them ideal for environmentally conscious applications (Kılınç and Korkmaz 2024). Among the most promising green composites are mycelium-based composites (MBCs), which use mycelium (the root structure of fungi) as a natural binding agent combined with organic substrates. These bio-composites are innovative materials that can be applied in various industries, including construction, as a sustainable alternative to synthetic materials (Aiduang *et al.* 2024a). Unlike traditional synthetic adhesives, mycelium acts as a self-assembling adhesive, forming a fibrous network of chitin and beta-glucan-based structural oligosaccharides (Jinanukul *et al.* 2024). This biological process allows mycelium to bind organic substrates, such as lignocellulosic byproducts (*e.g.*, sawdust, straw, husk, and stalk residues) (Aiduang *et al.* 2024a; Huang *et al.* 2024), effectively transforming waste into eco-friendly, biodegradable resources.

MBCs offer numerous environmental benefits, including low energy consumption, minimal processing costs, and a reduced carbon footprint, making them beneficial options for insulation materials as well as applications in packaging and foam replacements (Alemu *et al*. 2022; Voutetaki and Mpalaskas 2024; Huang *et al.* 2024). Previous studies have demonstrated that MBCs exhibit properties comparable to those of synthetic foams, wood-based products, and paper-based materials, showcasing their potential to replace traditional materials in multiple industries (Jones *et al.* 2020; Aiduang *et al.* 2024b; Teeraphantuvat *et al.* 2024). Furthermore, prior research by the authors has highlighted the advantages of using *Lentinus sajor-caju* fungal mycelium combined with corn husk to produce composites with excellent properties for building and insulation applications. These include great thermal insulation performance, low density, lightweight structure, biodegradability, and mechanical strength comparable to conventional materials such as polyimide, polystyrene, and polyurethane foams, making them particularly attractive for eco-friendly insulation boards (Aiduang *et al.* 2022; Jinanukul *et al.* 2024; Teeraphantuvat *et al.* 2024).

While MBCs show considerable promise, further investigation is needed to enhance their properties and overall quality (Alaneme *et al.* 2023). Specifically, an in-depth study focusing on the internal structure and physical properties of MBCs is essential for improving their uniformity and performance. Several studies suggest that MBCs exhibit excellent potential as insulation materials, with superior thermal conductivity, resistance, and heat capacity compared to traditional synthetic materials (Jones *et al.* 2020; Yang *et al.* 2021; Alaneme *et al*. 2023; Voutetaki and Mpalaskas 2024). However, detailed analysis of the internal structure and overall physical properties, such as density and thermal performance, is necessary to fully understand and optimize their capabilities.

This research aimed to provide a comprehensive examination of mycelium-based thermal insulation boards (MBI boards) produced from *L. sajor-caju* mycelium and corn husk at various thicknesses, focusing on their thermal insulation performance and physical characteristics, including density, microscopy analysis, thermal conductivity, resistance, and heat capacity. Based on our previous studies, this in-depth investigation will contribute significant insights into the development of MBCs, offering pathways for future quality enhancements in material technology. The findings are expected to guide the production of MBCs for optimal performance, helping to advance the adoption of MBCs in the construction industry.

EXPERIMENTAL

Substrate Preparation

In this study, the primary substrate used was corn husk (*Zea mays* L.), an agro-industrial waste sourced from agricultural areas in Chiang Mai province, Thailand. To provide uniformity, the husks were ground into small pieces and sieved to obtain particles ranging from 5 to 20 mm in size. The selected particles were then dried in a hot air oven at 60 °C for 24 h to remove residual moisture (reduced to 0%), thereby preparing them for further experimentation (Aiduang *et al.* 2022).

Fungal Mycelium Preparation

In this study, pure mycelium of *L. sajor-caju* was selected due to its continually positive performance in the authors' previous research, particularly in terms of structural and overall properties (Aiduang *et al.* 2022; Jinanukul *et al.* 2024; Teeraphantuvat *et al.* 2024). To prepare the mycelium for testing, it was cultured on potato dextrose agar (PDA; Conda, Madrid, Spain) at 30 °C for 7 days, allowing for optimal growth conditions before further experimentation.

Mycelium Inoculum Preparation

For mycelium inoculum preparation, sorghum seeds were used as the nutrient-rich substrate. The seeds were first boiled for 20 min, then allowed to cool at room temperature (between 25 to 28 °C). After cooling, 100 g of the boiled grains were transferred into glass bottles, which were sealed with cotton and aluminum foil. The bottles were then autoclaved at 121 °C for 20 min and allowed to cool for 24 h. Next, 1 × 1 cm^2 mycelial plugs were carefully taken from a pure *L. sajor-caju* culture grown on PDA and placed into the autoclaved bottles, with five plugs added per bottle. The inoculated bottles were incubated at 30 °C for two weeks to allow the mycelium to fully colonize the substrate (Aiduang *et al.* 2022).

Mycelium Cultivation on a Substrate

The mycelium cultivation process for this study was based on the methods outlined by Aiduang *et al*. (2022) and Jinanukul *et al*. (2024). To prepare the substrate, corn husk was mixed with several additives: 5% rice bran, 1% calcium carbonate, 2% calcium sulfate, and 0.2% sodium sulfate. Water was added to adjust the moisture content to achieve 60% relative humidity. A total of 500 g of the supplemented substrate were then packed into polypropylene bags, each measuring 3.5 inches (8.9 cm) in width and 12.5 inches (30.5 cm) in length. These bags were sealed and autoclaved at 121 °C for 60 min, then allowed to cool for 24 h. Once cooled, 5 g of prepared mycelial inoculum were added to each bag. The bags were incubated at 30 °C for 35 days to facilitate optimal mycelial growth.

Mold Design and MBI Boards Formation

Acrylic molds with dimensions of 350 mm × 350 mm and varying thicknesses (8, 16, and 24 mm) were used to form MBI boards in three practical thickness levels that are relevant and suitable for insulation applications. Prior to use, the molds were sterilized with 70% ethanol to preserve a clean surface. Each mold was then filled with 500, 1000, or 1500 g of fully colonized mycelium-substrate mixtures, corresponding to the selected board thickness. The filled molds were cold-pressed using a unidirectional press machine (Shop Press ZX0901E-1, New Taipei, Taiwan) at 2 MPa for 10 min to shape the boards. Post-pressing, the molds were incubated at 30 °C for three days to facilitate additional mycelial growth, then removed and incubated for another three days in plastic containers. Finally, the boards were dried in an oven at 70 °C for 72 h until a stable weight was reached, ensuring complete moisture removal (Jinanukul *et al.* 2024). An overview of the full production process is shown in Fig. 1.

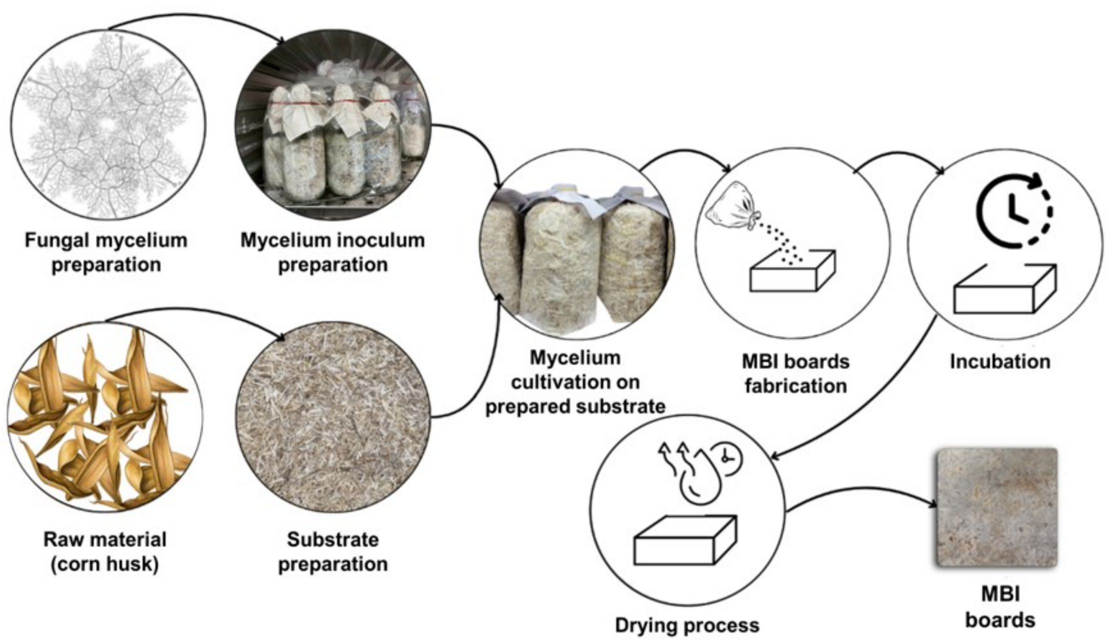


Fig. 1. An overview of the MBI boards production process in this study

Preparing the Specimen for Testing

In this study, the insulation performance and overall physical properties of the MBI boards were carefully evaluated to investigate the variability of mass per unit area of the obtained boards. For each test, final MBI board samples, measuring approximately 300 mm × 300 mm, were cut into 50 × 50 mm² specimens taken from three distinct positions on each board, corresponding to different thicknesses. These positions included the specimens closest to the edge (CE), those positioned midway between the centerline and edge (PM), and those nearest to the centerline (CC), with two specimens selected from each position, as illustrated in Fig. 2. The resulting specimens were then subjected to detailed assessments of their insulation performance and physical properties.

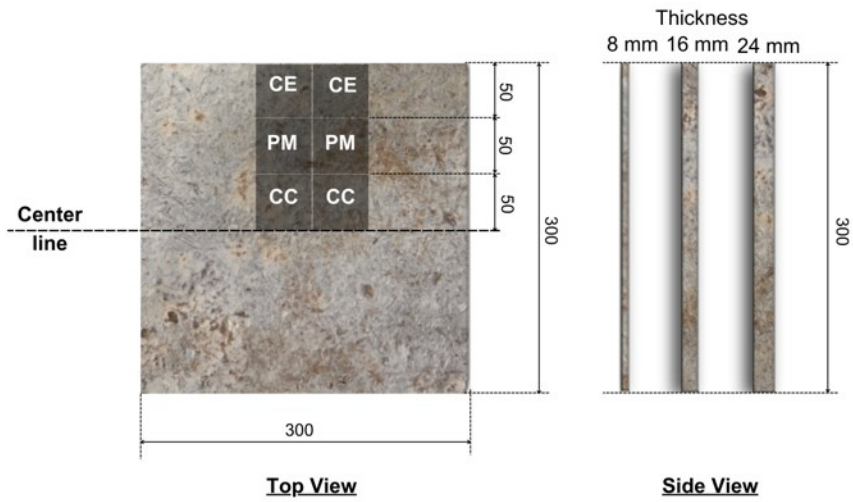


Fig. 2. Visual representation of MBC specimens at various positions across the board: CE indicates specimens taken closest to the edge, PM refers to those positioned midway between the centerline and the edge, and CC represents specimens closest to the centerline; All dimensional measurements are given in millimeters (mm).

Density Measurements

Density measurements were taken from various positions on each MBC specimen to calculate the average density of each developed board. The testing followed the guidelines established in British Standard BS EN 323:1993, as described in Eq. 1,

$$D = m/v \tag{1}$$

where D represents density in kilograms per cubic meter (kg/m³), m is the mass in kilograms (kg), and v is the volume in cubic meters (m³).

Thermal Conductivity and Thermal Resistance

Thermal conductivity testing was conducted following ISO 22007-2: 2022 using the hot wire method at room temperature. The measurements were performed with a Transient Hot Bridge apparatus (LINSEIS, THB-1), as illustrated in Fig. 3.

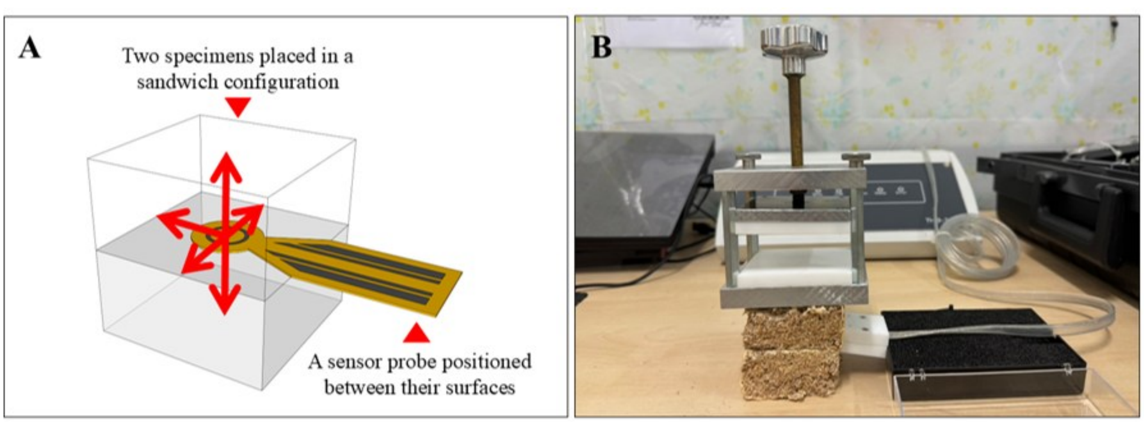


Fig. 3. Visual representation of MBC specimens at various positions across the board: CE indicates specimens taken closest to the edge, PM refers to those positioned midway between the centerline and the edge, and CC represents specimens closest to the centerline; All dimensional measurements are given in millimeters (mm).

Two specimens were placed in a sandwich configuration, with a sensor probe positioned between their surfaces to measure the heat transfer. Thermal resistance (R) was then calculated using Eq. 2,

$$R=\Delta x/k \quad (2)$$

where R is the thermal resistance ($m^2 \cdot K \cdot W^{-1}$), Δx is the specimen thickness (m), and k is the thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$).

Heat Capacity

The heat capacity of the MBI boards was determined using the Transient Hot Bridge (THB-1) technique (Jinanukul *et al*. 2024). First, both the MBC samples and a reference material with a known heat capacity were carefully prepared. After calibrating the THB-1 system, the reference material was mounted, followed by the MBC specimen, ensuring optimal thermal contact between them. The measurement was then initiated *via* THB-1 software (software LINSEIS, THB-1, Bavaria, Germany), which tracked temperature changes in both materials. Although the THB-1 software provides an initial estimate, a more accurate value is obtained by applying the following Eq. 3, using the temperature changes (ΔT_{ref} and $\Delta T_{\mathrm{sample}}$) recorded in the data file,

$$Cp_{\,sample}=\frac{m_{ref}\cdot Cp_{ref}\ (\Delta T_{ref}/\Delta T_{sample})}{m_{sample}} \quad (3)$$

where Cp_{sample} is the heat capacity of the MCI (kJ/kg·K), m_{ref} is the mass of the reference material (kg), Cp_{ref} is the known heat capacity of the reference material (kJ/kg·K), ΔT_{ref} is the temperature change of the reference material (K), and ΔT_{sample} is the temperature change of the MBI specimen (K).

Microscopy Optical Analysis

The MBC specimens were analyzed at various positions using a stereo microscope to examine their composition and structure, following a modified method based on Pycka and Roman (2023). Optical analysis was performed using a microscope (Nikon SMZ800N U, Tokyo, Japan), with data captured and recorded *via* a computer program. The resulting images were compared and analyzed in conjunction with the physical property assessments from other aspects of the study to confirm the uniformity of the material and to support the overall research findings.

Statistical Analysis

The experimental data were statistically analyzed using one-way analysis of variance (ANOVA) in SPSS software (version 22 for Windows, IBM, Chicago, IL, USA) to evaluate differences among treatment groups. Duncan's multiple range test was subsequently employed to determine significant differences between mean values at a confidence level of $p \leq 0.05$. Additionally, Pearson correlation coefficients (r) were calculated to assess the relationship between the distance from the center and the thickness of MBI boards in relation to their physical properties. All significance levels were set at $p < 0.05$, with analyses performed using SPSS.

RESULTS AND DISCUSSION

Density

The density of MBIs is influenced by a range of factors, including the substrate type and composition, particle size, mycelium strain, growth conditions, growth time, post-processing techniques, mold design, and drying conditions (Aiduang *et al.* 2024b; Teeraphantuvat *et al.* 2024). This study delved into the density variation of MBI boards produced using *L. sajor-caju* fungal mycelium combined with corn husk, specifically investigating the variability of mass within the boards at different positions. The results, shown in Fig. 4 indicated that density was not uniform across the entire board. The highest density was consistently observed in specimens closest to the centerline (CC) of the MBI boards, across all thicknesses. As the distance from the centerline increased, the density progressively decreased. Density values in this study ranged from 157 kg/m³ to 181 kg/m³. Additionally, it was observed that the density increased with board thickness, even at the same position.

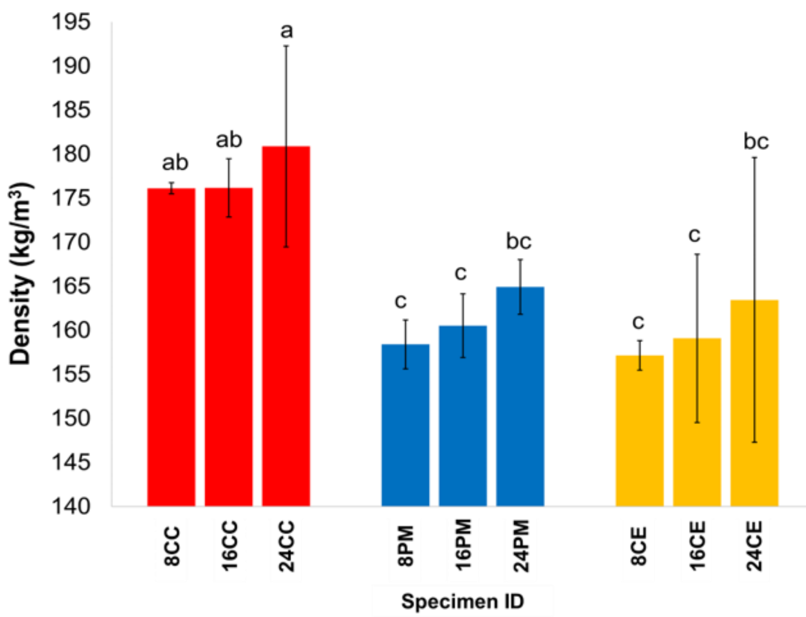


Fig. 4. Average density observed in this study, with red, blue, and yellow bars representing positions within the MBI boards: closest to the centerline (CC), midway (PM), and closest to the edge (CE), respectively. The number before each letter denotes board thickness. Different letters above bars indicate significant differences ($p \leq 0.05$) as determined by Duncan's multiple range test**.**

The observed density variation within the MBI boards can be attributed to several factors inherent in the production process, particularly the distribution of the substrate and mycelium growth patterns. The higher density near the centerline suggests a more efficient substrate distribution and a higher concentration of mycelium at the core. During mycelial growth, it tends to bind the substrate more tightly at the center, forming a denser network than the outer edges, where mycelial growth may be less concentrated (Soh and Le Ferrand 2023; Kohphaisansombat *et al.* 2024). This difference in mycelial colonization likely leads to the density gradient observed from the center to the outer edges of the board.

Furthermore, the increase in density with thicker boards is a predictable result, as thicker boards provide a greater volume for mycelium growth, allowing for a higher accumulation of mycelial biomass and substrate material. This trend, consistent with the authors' earlier findings, demonstrated that the density of MBCs tends to increase with increasing board thickness (Jinanukul *et al.* 2024). This result suggests that thicker MBI boards may offer more stability and better physical properties, which is advantageous for applications requiring higher strength and insulation performance. These findings align with the understanding that various factors, such as mycelium growth patterns, substrate composition, and processing conditions, play a crucial role in determining the final physical properties of MBCs (Aiduang *et al.* 2024a; Kohphaisansombat *et al.* 2024; Wattanavichean *et al*. 2025). Further research could focus on refining these parameters to achieve more uniform density distributions across MBI boards, enhancing the material's overall performance and reliability. Additionally, adjusting mycelial growth conditions and combining different substrate phases may help produce lower-density boards appropriate for specific building needs.

Thermal Conductivity

The thermal conductivity coefficient typically an important indicator when assessing the capability of a material to transport or limit heat flows across building insulation material (Anh and Pásztory 2021; Solubilityofthings 2025). In this study, thermal conductivity varied within the MBI boards site, ranging from 0.049 to 0.063 $W{\cdot}m^{-1}K^{-1}$, as shown in Fig. 5.

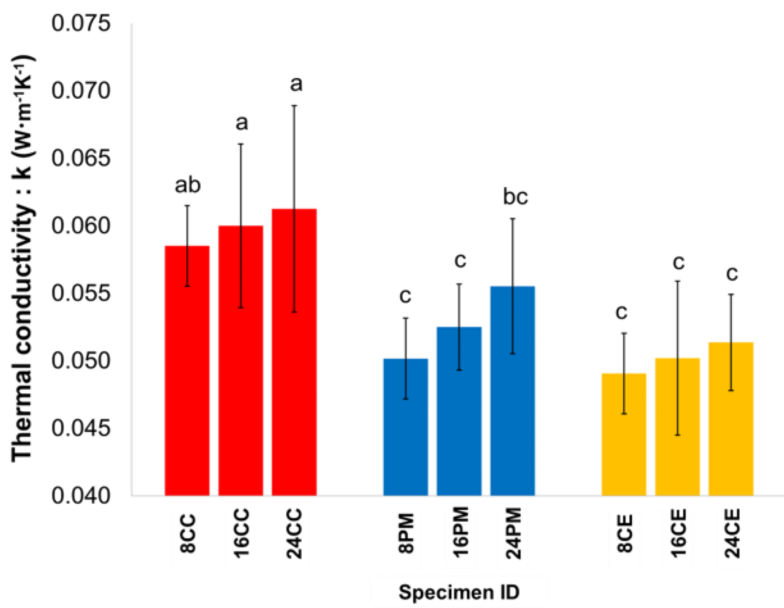


Fig. 5. The average thermal conductivity was observed in this study. The red, blue, and yellow bars represent positions within the MBI boards: closest to the center line (CC), midway between the center line and the edge (PM), and closest to the edge (CE), respectively. The number preceding each letter denotes the board thickness. Different letters above each bar indicate significant differences as determined by Duncan's multiple range test ($p \leq 0.05$).

At an 8-mm thickness, the centerline (CC) specimen recorded the highest conductivity of 0.059 $W{\cdot}m^{-1}{\cdot}K^{-1}$, while the midway point (PM) measured 0.050 and the edge (CE) the lowest at 0.049. When thickness increased to 16 mm, thermal conductivity rose slightly to 0.060 at CC, 0.052 at PM, and 0.050 at CE. The 24-mm boards showed a similar positional trend, with values of 0.063 at CC, 0.054 at PM, and 0.051 at CE. Thermal conductivity was highest in specimens closest to the centerline, across all thicknesses. This suggests that the thermal conductivity of MBI boards decreases as the distance from the edge increases, a trend that aligns with the density variations found in this study.

The variation in thermal conductivity across the MBI boards can be attributed to the density differences within the material (Alaneme *et al.* 2023), which were also noted in this study. Denser materials have significantly greater thermal conductivity because there are more tightly bound particles or molecules available to transfer energy (Haigh 2024). Areas close the centerline of the boards, which demonstrated higher density, also showed more effectively thermal conductivity. This is possibly due to the greater compact structure of the dense areas, which facilitates more efficient heat transfer. Conversely, the lower thermal conductivity at the outer edges of the boards corresponds to the lower density observed in those areas. Considering correlation between density and thermal conductivity supports the possibility that MBI boards' insulation properties are highly influenced by their internal structure. The decrease in thermal conductivity with increasing distance from the centerline suggests that optimizing the density distribution throughout the board could enhance its insulation performance. These findings indicate the importance of managing both the thickness and internal uniformity of MBI boards to improve their thermal efficiency. Future research could focus on refining manufacturing techniques to achieve more uniform density and thermal conductivity, which would further enhance the overall performance of MBI boards as eco-friendly, energy-efficient building materials.

Thermal Resistance

The average thermal resistance of the MBI boards increased continually with board thickness and varied markedly with position (Fig. 6).

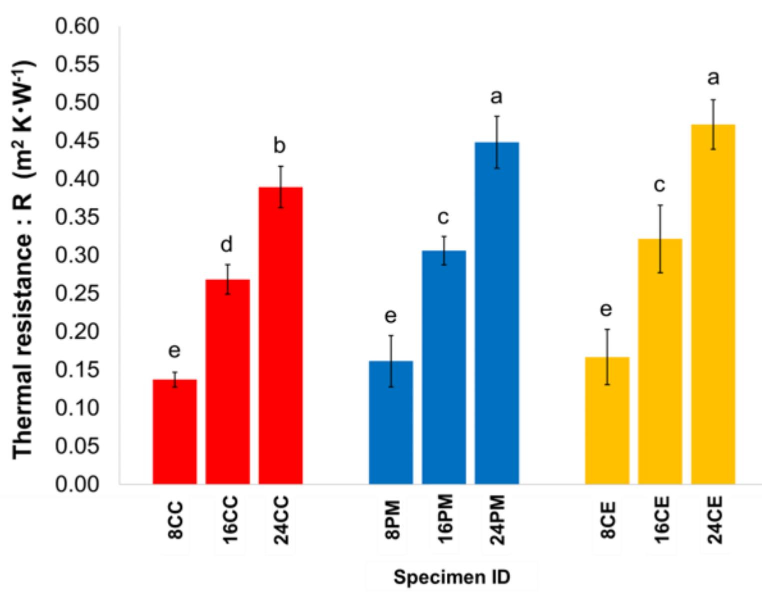


Fig. 6. The average thermal resistance was observed in this study. The red, blue, and yellow bars represent positions within the MCI: closest to the center line (CC), midway between the center line and the edge (PM), and closest to the edge (CE), respectively. The number preceding each letter denotes the board thickness. Different letters above each bar indicate significant differences as determined by Duncan's multiple range test ($p \leq 0.05$).

At 8 mm thickness, specimens closest to the centerline (8CC) exhibited the lowest resistance at approximately 0.137 m²·K·W⁻¹, while the midway (8PM) and edge (8CE) positions yielded slightly higher values of about 0.162 and 0.167 m²·K·W⁻¹, respectively. When the thickness was raised to 16 mm, thermal resistance climbed to roughly 0.268 m²·K·W⁻¹ at the centerline (16CC), 0.306 m²·K·W⁻¹ midway (16PM), and 0.322 m²·K·W⁻¹ at the edge (16CE). The thickest boards (24 mm) delivered the highest insulation performance, with average resistances of about 0.389 m²·K·W⁻¹ for 24CC, 0.448 m²·K·W⁻¹ for 24PM, and 0.471 m²·K·W⁻¹ for 24CE. Statistical analysis confirmed that each positional difference at 16 mm and 24 mm was significant, while the 8 mm boards showed smaller, non-significant variations. The trend of increasing thermal resistance from centerline toward the edge mirrors the inverse of the density distribution: denser cores (with densities up to 181 kg/m³ at 24CC) conduct heat more readily and thus exhibit lower resistance, whereas less dense edge points (down to 159 kg/m³ at 24CE) trap more air and resist heat flow more effectively. This positional dependence involves interplay between microstructure and insulation properties of MBI boards (Al-Qahtani *et al.* 2023). As board thickness increases, the cumulative thickness of insulating mycelial networks and air-filled pores enhances resistance, but the less compact outer layers consistently outperform the denser cores in thermal insulation, which closely correlate with the outcomes in previous studies (Fellah *et al.* 2021; De *et al.* 2025). These findings suggest that developing the mold design and mycelial colonization process to produce more consistent or purposely varied density distributions could optimize both the mechanical stability and thermal performance of MBI boards for eco-friendly green building applications.

Heat Capacity

The average heat capacity of the MBI boards remained remarkably uniform across both board thickness and position (Fig. 7), varying between 0.132 and 0.143 kJ/kg·K.

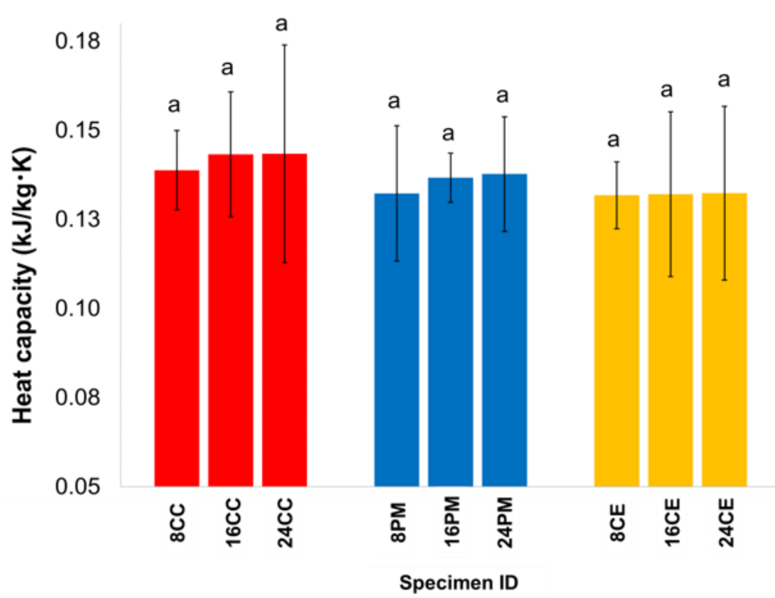


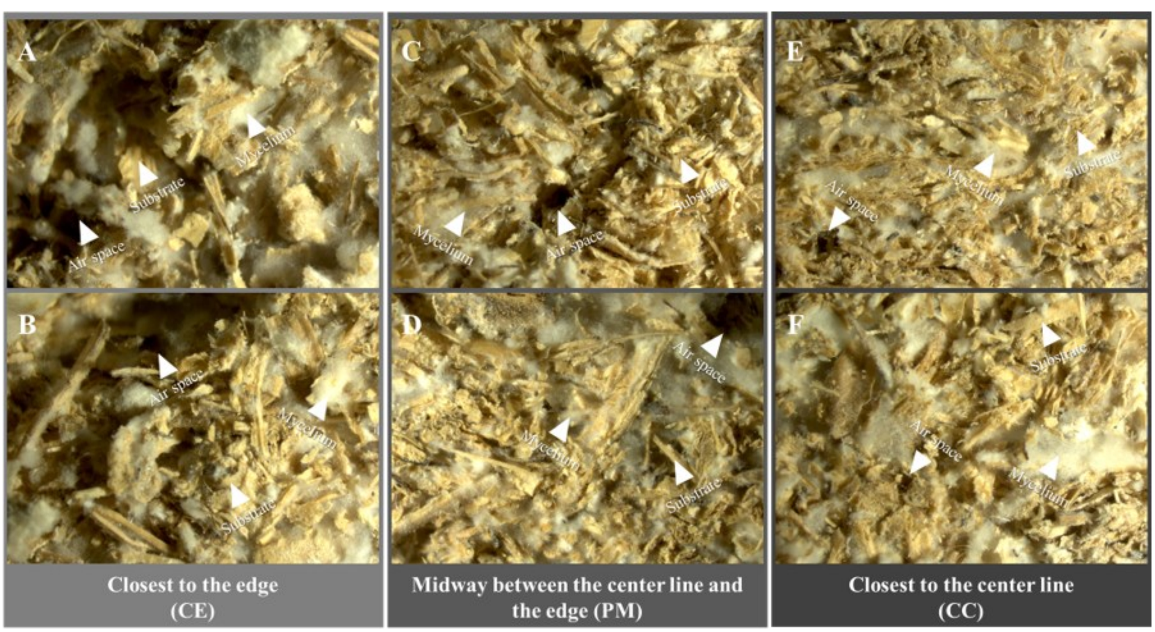
Fig. 7. The average heat capacity observed in this study. The red, blue, and yellow bars represent different positions within the MBI boards: closest to the center line (CC), midway between the center line and the edge (PM), and closest to the edge (CE), respectively. The number preceding each letter indicates the board thickness. Letters above each bar indicate significant differences based on Duncan's multiple range test ($p \leq 0.05$).

At 8 mm thickness, the centerline (CC) specimen registered a heat capacity of 0.139, while both the midway (PM) and edge (CE) specimens were at 0.132. When thickness was increased to 16 mm, CC rose modestly to 0.143, PM to 0.137, and CE remained at 0.132. The 24-mm boards showed a similar pattern: CC held at 0.143, PM at 0.138, and CE again at 0.132. This agreement suggests that the specific heat of the MBC material is largely independent of both thickness and position, reflecting an inherent thermal stability of the mycelium–corn husk matrix.

The minor rise near the centerline may be related to the slightly higher density observed present, because denser materials can store more thermal energy per unit mass (Tawalbeh *et al.* 2023). Conversely, the edge areas consistently displayed the lowest values, aligning with their lower density and potentially greater porosity (Alaneme *et al.* 2023). Overall, the findings indicate that although the thickness and density of MBI boards can be adjusted to adjust their insulation performance (through thermal resistance), their ability to absorb and retain heat is constant. This is a beneficial feature for applications that need consistent thermal balancing, like passively indoor environmental control.

Microscopically Assessed Results

Analysis by optical microscopy provided insightful details into the internal microstructure of the MBI boards at different positions (Fig. 8), revealing clear spatial variations that strongly influence their physical and thermal properties. At the centerline position (CC), the internal structure appeared highly compact, showing a dense matrix of fungal mycelium interwoven tightly with the corn husk substrate, leaving minimal air space. In contrast, the specimens located closest to the edge (CE) exhibited a noticeably looser structure. These edge samples displayed a lower-density matrix phase (mycelium) as well as less widely distributed substrate particles, resulting in larger internal voids and greater air space. This more porous structure directly correlates with reduced density and improved insulation performance due to the insulating properties of trapped air. The PM specimens, located between the center and edge, demonstrated intermediate characteristics, a moderate level of mycelial density and substrate distribution, with more air space than the CC but less than the CE.



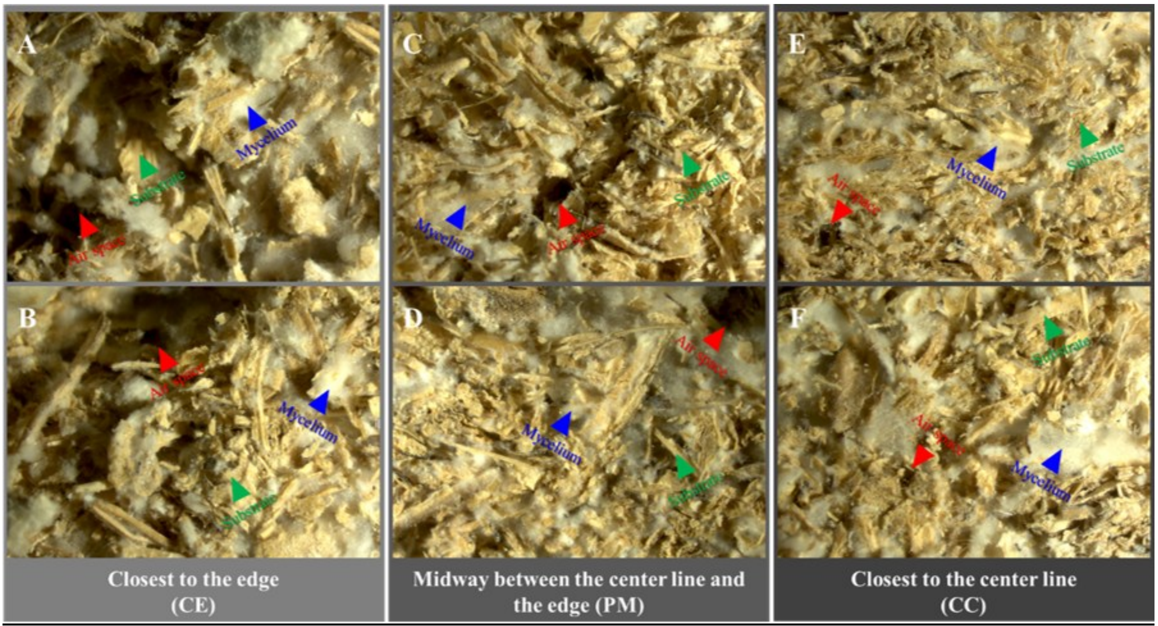


Fig. 8. Detailed photographs into the internal microstructure of MBI boards at various positions, analyzed through optical microscopy

Overall, the internal morphology of the MBI boards can be described as a composite consisting of three key components: the matrix-phase (mycelium), the dispersed-phase (corn husk substrate), and internal air space (Aiduang *et al.* 2024a; Teeraphantuvat *et al.* 2024). These structural components varied significantly by position, with the center providing the strongest combination for thermal insulation and structural integrity. This internal structure gradient from center to edge directly corresponds to measured changes in physical properties such as density, thermal conductivity, and thermal resistance. The findings indicate the critical role of mycelial distribution and compaction in determining MBC performance. The microscopic insights also provide a useful explanation for the positional dependence of thermal performance in MBI boards and provide recommendations for enhancing manufacturing processes to produce more reliable and effective bio-insulating materials.

Analyzing the Pearson Correlation Coefficient and Comparing its Quality

The Pearson correlation analysis offered important information on the effects of thickness and spatial position (distance from the edge) on the thermal and physical properties of MBI boards. From Table 1, a strong and statistically significant negative correlation was observed between density and distance from the edge at 8 mm ($r = -0.750$, $p = 0.020$) and 16 mm ($r = -0.858$, $p = 0.003$), suggesting that MBC specimens become less dense toward the outer edge. This trend decreased at 24 mm thickness ($r = -0.599$, $p = 0.089$), which was likely due to more uniform colonization and development at higher substrate volumes. In contrast, thermal conductivity and thermal resistance both showed very strong, significant positive correlations with distance from the edge across all thickness levels, especially for 24 mm boards ($r = 0.966$ and $r = 0.968$, respectively, $p < 0.001$). These findings suggest that insulation performance improves as one moves outward from the denser core to the edge, likely due to reduced density and increased air entrapment. It is worth mentioning that heat capacity showed no significant correlation with position, indicating that this property remained relatively stable across the MBC structure.

Table 1. Pearson Correlation Coefficients between the Properties and a Distance from the Edge of the MBI Boards with the Same Thickness

Properties	Pearson Correlation Coefficients (r / p-value)		
	8 mm	16 mm	24 mm
Density	-0.750*/ 0.020	-0.858*/ 0.003	-0.599/ 0.089
Thermal Conductivity	0.915*/ < 0.001	0.938*/ < 0.001	0.966*/ < 0.001
Thermal Resistance	0.937*/ < 0.001	0.956*/ < 0.001	0.968*/ < 0.001
Heat Capacity	-0.163/ 0.676	-0.351/ 0.354	-0.265/ 0.491

"*" Indicates a significant correlation at a significance level of $p < 0.05$. r = Pearson correlation coefficients

When considering Table 2, the effect of increasing thickness on thermal resistance was strongly positive and statistically significant across all positions (CE, PM, and CC), with r = 0.999 and p < 0.001. This confirms that increasing thickness directly improved insulation performance, as thicker MBI boards trap more air and provide longer heat move paths. While density only showed a significant positive correlation with thickness at the centerline position (CC, r = 0.713, p = 0.031), the edge and midway positions did not follow this trend. This suggests that higher density due to compaction or nature during growth tends to be located more at the core, while outer zones remain lighter and more porous, improving their insulation properties.

Table 2. Pearson Correlation Coefficients Between the Properties and an Increase in Thickness of the MBI Boards with the Same Thickness Position

Properties	**Pearson Correlation Coefficients (*r* / *p*-value)**		
	CE	**PM**	**CC**
Density	0.256/ 0.507	0.465/ 0.208	0.713*/ 0.031
Thermal Conductivity	0.149/ 0.458	0.300/0.128	0.915/0.443
Thermal Resistance	0.999*/ < 0.001	0.999*/ < 0.001	0.999*/ < 0.001
Heat Capacity	0.070/ 0.858	0.156/ 0.687	0.163/ 0.674

"*" Indicates a significant correlation at a significance level of $p < 0.05$. The Pearson correlation coefficients (*r*) are as follows: Specimen ID - CE refers to the closest point to the edge, PM is positioned midway between the center line and the edge of the MBI, and CC is the closest point to the center line. The unit of measurement is in millimeters (mm).

In Table 3, comparing MBI board properties with conventional insulation materials highlights their competitive performance. For instance, the thermal conductivity of 24 mm MBI board at the edge (0.051 $W·m^{-1}·K^{-1}$) was close to that of rock wool and glass fiber. Though MBI board has higher density than most commercial insulators, its thermal resistance of 0.471 $m^2·K·W^{-1}$ for the 24CE specimen approaches the lower range of conventional options. However, MBI boards offer an environmentally sustainable alternative with bio-based composition and biodegradable potential. Additionally, the minimal variation in heat capacity across thicknesses and positions suggests that MBI board maintains a consistent thermal property, potentially advantageous for adjusting the indoor climate.

Table 3. Comparison of Thermal Properties Between MBI Boards and Conventional Materials

Material	Properties			
	Density (kg/m^3)	**Thermal Conductivity ($W·m^{-1}K^{-1}$)**	**Thermal Resistance (m^2 $K·W^{-1}$)**	**Heat Capacity (kJ/kg-C)**
In this study				
MBI 8 mm. thick				
• CC	176.1	0.059	0.137	0.139
• PM	158.4	0.050	0.162	0.132
• CE	157.2	0.049	0.167	0.132
MBI 16 mm. thick				
• CC	176.2	0.060	0.268	0.143
• PM	160.5	0.052	0.306	0.137
• CE	159.2	0.050	0.322	0.132
MBI 24 mm. thick				
• CC	181.0	0.063	0.389	0.143
• PM	164.9	0.054	0.448	0.138
• CE	163.6	0.051	0.471	0.132
Conventional material*				
• Glass fiber insulation	6.4 to 9.6	0.049 to 0.055	0.454 to 0.510	-
• Rock and slag wool insulation	24 to 29	0.046 to 0.049	0.510 to 0.543	-
• Cellulose fiber insulation	16 to 19	0.045 to 0.046	0.544 to 0.556	-
• Vermiculite, exfoliated insulation	64 to 131	0.063 to 0.068	0.397 to 0.368	1.3
• Polyurethane foam	7.2 to 10	0.037 to 0.042	0.595 to 0.676	1.5

Note: Specimen ID definitions: CE refers to specimens located closest to the edge, PM refers to those positioned midway between the centerline and the edge of the MBI boards, and CC refers to specimens located closest to the centerline. All measurements are in millimeters (mm). *References: Lewis (1967); Sabine and Lacher (1975); Valore (1988); Kumaran *et al.* (2002); Ashrae (2021)

In summary, the Pearson correlation analysis supports the observation that position and thickness significantly affected the thermal performance of the MBI boards. Higher thickness and positioning towards the edge consistently enhanced thermal resistance, correlating inversely with density and directly with insulation performance. This suggests strategic manipulation of growth parameters could lead to optimized, high-performance, and eco-friendly insulation panels. Future quality enhancements should focus on achieving more uniform mycelial colonization and substrate distribution during growth, particularly through optimized mold design, growth conditions, and post-processing. These improvements are expected to contribute to the development of high-performance, bio-based insulation boards that are both sustainable and effective for modern construction needs.

FUTURE WORK

Based on the outcomes of this study, additional research and challenges should be focused on enhancing MBI's internal uniformity and performance by way of the following essential approaches:

1. Optimization of substrate formulation: Investigate the influence of different substrate compositions, including alternative agricultural residues or additive blends, to improve mycelial colonization uniformity and thermal performance.
2. Mold and inoculation design: Develop and test innovative mold designs and inoculation techniques that promote more even mycelial spreading, reducing edge-to-center density variation.
3. Multi-layered or graded structure design: Explore the feasibility of designing composite MBI boards with intentional layering or density grading to achieve targeted thermal or mechanical performance.
4. Life cycle and economic assessment: Perform a comprehensive life cycle assessment (LCA) and cost-benefit analysis to benchmark MBI performance against conventional insulation materials in terms of environmental and economic viability.
5. Microstructural analysis using SEM: Propose to investigate fiber morphology using Scanning Electron Microscopy (SEM) in future studies to explore the relationship between fiber thickness, material density, and insulation performance in greater detail.

These directions aim to guide the development of high-quality, consistent, and scalable mycelium-based insulation systems that meet the demands of sustainable construction and green building standards

CONCLUSIONS

1. The internal density of mycelium-based insulation (MBI) boards exhibited non-uniformity, which was strongly influenced by mycelial growth patterns. The highest densities were consistently located at the centerline (*e.g.*, 181 kg/m^3 at 24CC), with values progressively decreasing toward the edges (down to 157 kg/m^3).
2. Thermal conductivity ranged from 0.049 to 0.063 W·m^{-1}·K^{-1}, increasing with both thickness and density. The centerline showed the highest conductivity, reflecting its denser structure.
3. Thermal resistance increased with increased board thickness and distance from the centerline. The highest resistance (0.471 m^2·K·W^{-1}) was observed at 24 mm (24CE), which was likely due to lower density and greater air entrapment, which enhance insulation performance.
4. Specific heat capacity remained relatively constant (0.132 to 0.143 kJ/kg·K) across all thicknesses and positions, suggesting stable thermal energy absorption throughout the MBI board's structure.
5. Microscopic analysis validated macro-level trends, revealing denser matrix structures at the center and more porous, air-filled structures near the edges.

6. Pearson correlation analysis showed strong positive correlation between distance from edge and thermal resistance at 24 mm ($r = 0.968$, $p < 0.001$), and a significant negative correlation between density and edge distance at 16 mm ($r = -0.858$, $p = 0.003$).
7. These findings highlight the necessity for quality enhancements and demonstrate the competitive insulating properties of MBI boards when compared to conventional materials (such as rock wool).

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