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Article

Bio-Based Insulation Panel from Rice Husk Residues for Thermal Resilience in Sustainable Buildings

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Abstract: As buildings face growing exposure to climate-induced stressors such as heatwaves, energy demand spikes, and humidity fluctuations, rethinking insulation strategies become crucial to achieving thermal resilience and energy efficiency. Conventional insulation materials often rely on non-renewable resources and exhibit poor environmental performance, highlighting the urgent need for sustainable alternatives in building applications. This study aims to develop an eco-efficient thermal insulation material derived from agricultural residues to support climate-adaptive and low-carbon building practices. A bio-based thermal insulation panel composed of rice husk fiber was fabricated using polyvinyl alcohol (PVOH) as a binder, with formulations containing 0%, 5%, 10%, and 15% PVOH by weight. The prepared panels were evaluated for their mechanical strength, dimensional stability, and thermal conductivity. Experimental results indicate that the thermal insulation panel formulation containing 10% PVOH is optimal, exhibiting superior mechanical properties with a flexural strength of 9.822 MPa, a tensile strength of 4.369 MPa, and an internal bond strength of 0.038 MPa. Water absorption and thickness swelling were recorded at 92.13% and 33.61%, respectively, confirming good moisture stability. The best-performing sample achieved the lowest thermal conductivity of 0.245 W/m·K, indicating strong insulation potential. The findings highlight the viability of agricultural waste as a raw material for bio-insulation panels, offering both environmental and performance benefits. By reducing dependency on synthetic materials and enhancing indoor thermal comfort, this bio-based thermal insulation panel contributes to the design of resilient, low-carbon buildings capable of adapting to future climate conditions.

Keywords: Natural waste fibers; resource sustainability; rice husk residue; thermal insulation

1. Introduction

The increasing impacts of climate change and rising building energy demand have intensified the need for sustainable and high-performance construction materials that can enhance thermal resilience and indoor environmental comfort. As cooling energy demand continues to rise, the performance and sustainability of insulation materials become increasingly critical for achieving thermal resilience and reducing operational carbon emissions (Shakir et al., 2025b; Shaah et al., 2021). However, conventional insulation materials such as expanded polystyrene (EPS), polyurethane foam and mineral wool, rely heavily on non-renewable petrochemical resources and exhibit poor end-of-life sustainability, generating significant environmental burdens during production and disposal (Asdrubali et al., 2015; Azamzam et al., 2022). These limitations highlight the urgent need for innovative, low-carbon insulation materials capable of delivering effective thermal performance while supporting global decarbonization goals in the building sector.

Agricultural residues such as rice husk and sawdust represent abundant lignocellulosic by-products commonly generated in rice milling and timber industries. These wastes are frequently underutilized or disposed of through open burning, contributing to air pollution and greenhouse gas emissions (Chavan et al., 2022). Structurally, rice husk is composed mainly of cellulose (35–40%), hemicellulose (20–25%), lignin (15–25%), and a considerable amount of silica (15–20%), which contributes to its rigidity and thermal stability. The presence of silica in rice husk also enhances resistance to biological degradation and improves dimensional stability when incorporated into composite materials (Ishida et al., 2025). These components provide a porous microstructure capable of trapping air within the composite matrix, thereby reducing heat transfer and improving insulation performance (Mbishida, 2020).

Biocomposites reinforced with natural fibers have emerged as viable alternatives to synthetic insulation due to their renewability, biodegradability, and lower embodied energy (Ahmad et al., 2022). Biocomposites reinforced with lignocellulosic wastes such as rice husk serve as promising sustainable thermal insulation panels for buildings. These materials offer low thermal conductivity, lightweight characteristics, and environmental advantages such as waste valorization and reduced embodied carbon compared to synthetic foams (Cigarruista Solís et al., 2024a). The parameters influencing their thermal and mechanical performance include biocomposite density and porosity, fiber content and geometry, binder type and proportion, fiber-matrix bonding, and processing conditions (Pawłosik et al., 2025). When combined with polymeric binders, lignocellulosic particles can form structurally stable biocomposites with enhanced mechanical integrity and improved resistance to moisture degradation. Polyvinyl alcohol is widely recognized for its excellent film-forming ability, hydrophilicity, and compatibility with biomass fibers, enabling improved bonding at the fiber–matrix interface (Tan et al., 2015, Shakir et al., 2025c). Prior studies have shown that optimizing binder concentration can significantly influence mechanical strength, dimensional stability, and thermal conductivity of fiber-reinforced composites (Elmoudnia et al., 2025). Despite these advancements, balancing thermal insulation, moisture resistance, and mechanical durability remains a key challenge in developing building-grade bio-insulation materials.

Despite the growing interest in lignocellulosic biocomposites for building insulation, existing studies have primarily focused on single-property optimization such as thermal conductivity or mechanical strength with limited attention given to achieving a balanced combination of thermal performance, moisture stability, and structural durability required for building envelope applications. The influence of binder concentration on the integrated performance of rice husk-based biocomposites remains insufficiently explored. Most have either examined a limited range of binder contents or evaluated only isolated performance metrics, without systematically optimizing for the integrated combination of mechanical strength, dimensional stability under humid conditions, and thermal insulation performance required for building applications. Therefore, further investigation is required to develop optimized bio-based insulation materials that simultaneously enhance thermal efficiency, dimensional stability, and mechanical reliability while utilizing agricultural waste as a sustainable raw material.

Therefore, this study develops a rice husk–biobased panel using polyvinyl alcohol as a binder and systematically evaluates its mechanical, dimensional, microstructural, and thermal performance to identify an optimized formulation suitable for sustainable building insulation. By valorizing agricultural waste into functional insulation panels, the proposed material contributes to the development of low-carbon and resource-efficient building materials aligned with circular economy principles in the built environment.

2. Materials and methods

2.1. Preparation of rice husk fiber

Rice husk (RH) fiber was collected from a local rice mill located in Seberang Perai, Penang, Malaysia. Polyvinyl alcohol (PVA) powder (85,000–124,000 g/mol, 99% hydrolyzed) was obtained from R&M Chemicals (Malaysia), while citric acid (analytical grade) was supplied by Sigma-Aldrich (Malaysia). Prior to thermal insulation panel fabrication, the RH fibers were thoroughly cleaned with distilled water to remove impurities such as dust, silica residues, and other contaminants. The cleaned fibers were subsequently dried in a laboratory oven at 100 °C until a moisture content of approximately 10% was achieved, as determined using a moisture analyzer. The dried RH fibers were then stored in sealed containers under ambient laboratory conditions to prevent moisture absorption prior to thermal insulation panel fabrication.

2.2. Fabrication of thermal insulation panel

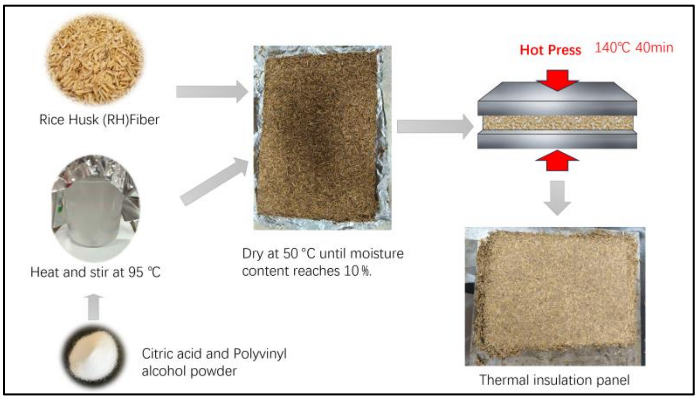

Figure 1. Schematic diagram of the fabrication process for RH–PVOH thermal insulation panel

Figure 1 illustrates the schematic diagram of the fabrication process for the RH–PVOH thermal insulation panels. For each formulation, RH fibers were blended with different proportions of PVOH binder at 0%, 5%, 10%, and 15% based on the total thermal insulation panel weight. The PVOH powder was first dissolved in distilled water at 95 °C under continuous magnetic stirring until a clear and homogeneous solution was obtained. A small amount of citric acid (0.5 wt% relative to PVOH) was added to the PVOH solution as a crosslinking agent to enhance solution stability and promote better interfacial interaction between PVOH and rice husk fibers. The prepared PVOH solution was then uniformly sprayed onto the RH fibers while continuously mixing to ensure homogeneous distribution of the binder throughout the fiber matrix.

The resulting RH–PVOH mixture was subsequently pre-dried in an oven at 55 °C for 8 h to remove excess moisture and prevent binder exudation during the hot-pressing process. Bio-based thermal insulation panels were then fabricated using a hot-press molding technique. The pre-dried mixture was placed into a mold with dimensions of 300 mm × 210 mm × 6 mm and hot-pressed at 140 °C under a pressure of 3 MPa for 40 min using a laboratory hot-press machine (TMAX-RYJ-D600F Laboratory Electronic Industry Wide-Flat Automatic Hot Press Machine). After pressing, the panels were allowed to cool to room temperature while maintaining pressure to minimize panel warping and delamination. All panels were fabricated with a target density of 0.8 g/cm^3.

2.3. Physicochemical, Mechanical and Thermal Characterisation

2.3.1. Fourier Transformation Infrared Analysis

Functional group identification was carried out using a Fourier transform infrared spectrometer (FTIR, Bruker Tensor 27, using KBr pellet technique, in the range of 4000-400 cm^{-1} with a resolution of 4 cm^{-1} and 40 cumulative scans) to identify characteristic peaks such as hydroxyl groups, carbon oxygen bonds and aromatic rings (Wang et al., 2022).

2.3.2. Mechanical and Physical Evaluation

Flexural, tensile, and internal bond strength properties were measured using a Comtech QC-506 M1 universal testing machine according to ASTM D790, ASTM D638, and JIS A5908 (2003), respectively. The span length was set at 120 mm, and the machine applied a uniaxial load at a constant crosshead speed of 3 mm/min until specimen failure.

The flexural strength (σ_f) was calculated using Equation (1):

$$\sigma_f = 3PL/2bd^2 \quad (1)$$

where σf is the flexural strength of sample, MPa; P is the maximum load, N; L is span length, mm; b is width of the sample, mm; and t is the thickness of sample, mm.

The tensile strength (σ_t) was calculated using Equation (2):

$$\sigma_t = F_{max}/A \quad (2)$$

where σt is Tensile strength of sample, MPa; F_{max} is Maximum load, A is Average cross-sectional area of sample.

The internal bond strength (I_B) was calculated using Equation (3):

$$I_B = P'/2bL \quad (3)$$

where, P' is maximum load (N) at the time of failing force; b is width (mm) of sample; Lis length (mm) of sample.

The impact strength will be determined using a cantilever beam impact tester with a 5.5J pendulum according to ASTM D256. Each combination of fiber and substrate will be tested five times, and the average value will be taken as the result.

$$I_s = E/A \quad (4)$$

where E is impact energy (J), mgh, A is impact area (mm²)

2.3.3. Water Absorption

The water absorption of the thermal insulation panels was determined according to JIS A5908 (2003). Four thermal insulation panel formulations were evaluated in this study. For each formulation, four replicate samples were prepared and conditioned at room temperature for 24 h prior to testing. The samples were then immersed in water to a depth of approximately 30 mm below the water surface for 24 h. The mass of each sample before and after immersion was measured using a digital balance with an accuracy of ±0.0001 g to determine water absorption. The percentage of water absorption was calculated using Equation (5):

$$W_{abs} = \frac{W_{bc} - W_{ac}}{W_{ic}} \times 100 \quad (5)$$

where W_{abs} is the total percentage of water absorption of panel, %; W_{bc} is the weight of panel before water immersion, g; W_{ac} is the weight of panel after water immersion, g; and W_{ic} is the initial weight of panel, g.

2.3.4. Thickness swelling

The thickness swelling of the thermal insulation panels was also evaluated according to the procedure described in JIS A5908 (2003). Four thermal insulation panel formulations were tested, and five replicate specimens were prepared for each formulation. The samples were immersed in water for 24 h under the same conditions used in the water absorption test. The thickness of each specimen was measured before and after immersion using a digital vernier caliper with a precision of ±0.001 mm. The percentage of thickness swelling was calculated using Equation (6):

$$T_{ats} = \frac{T_{bts} - T_{afs}}{T_{its}} \times 100 \quad (6)$$

where T_{ats} is the total percentage of thickness swelling of thermal insulation panel, %; T_{bts} is the thickness of panel before placed into the chamber, mm; T_{afs} is the thickness of panel after removal from the chamber, mm; and T_{its} is the initial thickness of panel, mm.

2.3.5. Thermal conductivity analysis

The thermal conductivity of the RH–PVOH thermal insulation panels were measured using the transient plane source (TPS) method. The optimal thermal insulation panel samples were tested using a Hot Disk Thermal Constants Analyzer (TPS 2500). The test was performed according to ASTM C1045–07. Measurements were conducted at room temperature (20–25 °C) under controlled humidity. The measurement principle was based on recording the transient temperature rise of the sensor when an electrical current passed through it. By analyzing the temperature–time response and the power input, the thermal conductivity (k) of each sample was automatically calculated by the TPS 2500 software.

3. Results

3.1. Fourier Transformation Infrared

Figure 2 shows the FTIR spectra of the RH–PVOH biobased thermal insulation panels with different PVOH contents (0%, 5%, 10%, and 15%). The analysis was conducted to identify the characteristic functional groups present in the panels and to evaluate the interfacial interactions between rice husk fibers and the PVOH matrix.

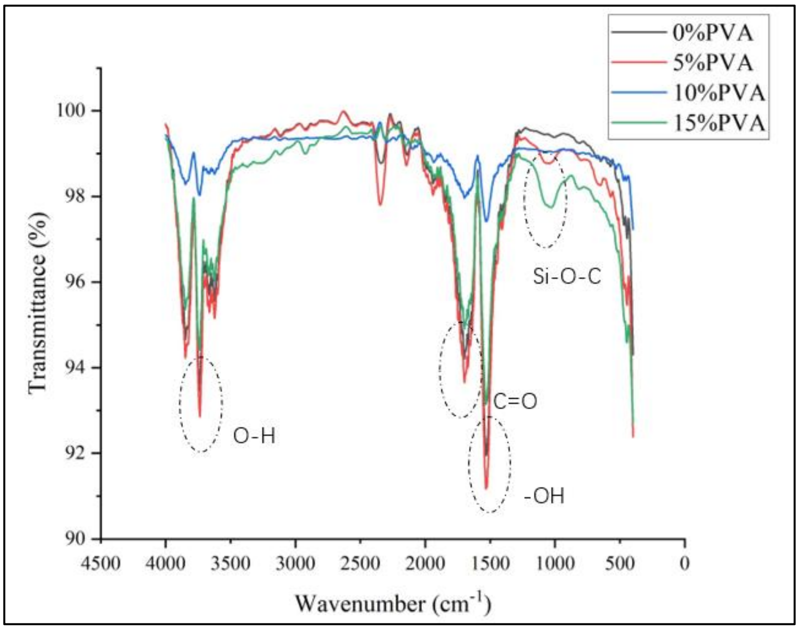

Figure 2. The FTIR trend peak and intensity of each functional group

The FTIR spectra revealed several characteristic absorption bands corresponding to the functional groups of RH fibers and the modifications introduced by PVOH. The strong and broad absorption band at 3200–3600 cm^{-1}, together with the weak band at 1100–1200 cm^{-1}, represents the O–H stretching and C–O–C glycosidic bonds of cellulose and hemicellulose, respectively. The intensity of the hydroxyl band indicates a high content of polysaccharides in the raw fiber. With the incorporation of PVOH, notable spectral changes were observed. The absorption band near 1720–1730 cm^{-1}, corresponding to C=O stretching, became more pronounced to PVOH contained in biobased panels. This increase is associated with residual acetate groups of partially hydrolyzed PVOH and possible oxidation during processing (Daw et al., 2025, Chan et al., 2022). No significant shifts in the position of the C=O band were observed that would clearly indicate the formation of new chemical bonds.

Notably, the intensity of this band did not increase linearly with increasing PVOH content. The 5% PVOH sample exhibited the strongest C=O peak, followed by the 15% and 10% PVOH samples. This non-linear trend may reflect differences in the local environment or accessibility of the carbonyl groups at different PVOH loadings. However, the FTIR data does not provide clear evidence of new chemical bond formation. The primary interaction between PVOH and rice husk fibers is expected to occur through physical hydrogen bonding between the hydroxyl groups of PVOH and the hydroxyl/carboxyl groups on the lignocellulosic fiber surface (Wang et al., 2022, Saksornchai, 2023). In addition to these changes, the band within the 1000–1100 cm^{-1} region assigned to Si–O–C and Si–O–Si vibrations from the silica inherently present in rice husk persisted across all samples. This indicates that PVOH addition does not affect the inorganic silica structure of the fiber.

Slight shifts in this region with increasing PVOH content suggest minor modifications in the local bonding environment at the fiber-matrix interface, consistent with physical rather than covalent interactions. Furthermore, the peak around 1200-1300 cm^{-1}, associated with C–O stretching and secondary alcohol groups, exhibited increased intensity in the biobased panel containing PVOH. This enhancement reflects successful mixing and partial penetration of PVOH polymer chains into the cellulosic matrix. The FTIR results confirm that PVOH interacts effectively with RH fibers primarily through hydrogen bonding between the hydroxyl groups of PVOH and the hydroxyl/carboxyl groups on the rice husk fiber surface. Although esterification between PVOH and citric acid (or rice husk carboxyl groups) may occur to a limited extent under hot-pressing conditions, no clear peak shifts or new ester carbonyl peaks indicative of significant chemical bonding was observed. Therefore, physical hydrogen bonding is considered the dominant interaction mechanism in this study. The progressive increase in the intensity of the O–H, C–O, and C=O functional groups with higher PVOH content indicates improved compatibility and enhanced interfacial bonding between the fiber and the polymer matrix. This improved interaction supports the mechanical performance improvements observed in the biobased panels.

3.2. Water absorption and thickness swelling

The water absorption and thickness swelling behavior of the thermal insulation panels varied with the PVOH content, as illustrated in Figure 3. At 5% PVOH, the panels exhibited a water absorption of 120.67% and a thickness swelling of 35.91%, indicating a high level of water uptake and considerable dimensional instability. When the PVOH content was increased to 10%, both parameters showed noticeable improvement, with water absorption reduced to 92.13% and thickness swelling significantly decreased to 33.61%. This improvement suggests that intermediate PVOH content contributes to better matrix consolidation and reduced void formation, thereby limiting water penetration into the biobased panel structure. However, when the PVOH content was further increased to 15%, a slight decline in material performance was observed, with water absorption rising to 93.89% and thickness swelling reaching 34.66%. This behavior may be associated with the hydrophilic nature of PVOH, where excessive polymer content can promote moisture interaction and compromise the dimensional stability of the biobased panels.

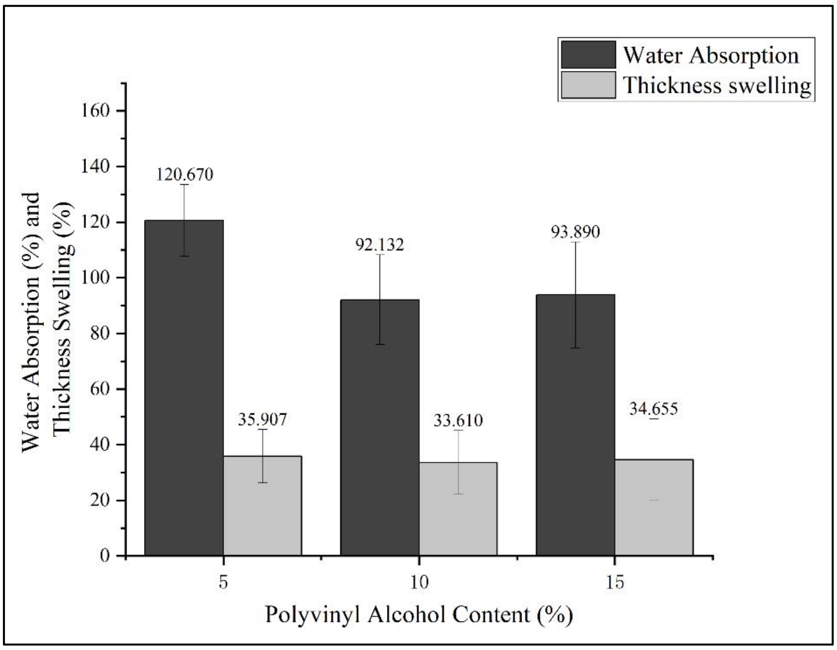

Figure 3. Effect of PVOH content on the water absorption and thickness swelling behavior of the biobased thermal insulation panels

The deterioration at higher PVOH loading may be attributed to the hydrophilic nature of PVOH, which increases moisture affinity when present in excessive amounts. Additionally, too much PVOH may form localized polymer clusters, prevent uniform coating of the fibers, and lead to microvoid formation that facilitates water absorption. This observed trend is consistent with previous studies on rice husk–PVOH or rice husk–reinforced polymer biocomposites. Wang et al. (2022) reported that blending rice husk with 20% PVOH reduced water uptake by approximately 50% (from 30% for untreated rice husk plates to 14.4% for the PVOH-blended biocomposite) after 24 h immersion, attributing the improvement to the formation of a continuous PVOH coating that acts as a diffusion barrier and to extensive hydrogen bonding between PVOH hydroxyl groups and the lignocellulosic surface, which restricts water molecule penetration (Wang et al., 2022).

Similarly, Pakravan et al. (2018) observed significantly lower water absorption in cementitious biocomposites incorporating ground rice husk combined with PVOH fibers, with the reduction linked to enhanced interfacial bonding and decreased porosity at optimal filler-binder ratios (Pakravan et al., 2018). In PVOH film systems, Cholant et al. (2025) demonstrated that reinforcement with rice husk–derived nanocellulose resulted in the lowest solubility and water vapor permeability among tested formulations, due to strong hydrogen bonding networks that limit hydrophilic pathways (Cholant et al., 2025). These findings collectively confirm that optimal binder/reinforcement concentrations (typically 10–20 wt%) effectively mitigate water absorption in agricultural waste–based biocomposites by improving compatibility, sealing microvoids, and reducing available hydroxyl sites for water interaction.

3.3. Mechanical testing result

3.3.1. Flexural strength

As shown in Figure 4, the flexural strength (modulus of rupture, MOR) of the RH–PVOH biobased panels increased with PVOH content. The control sample (0% PVOH) exhibited the lowest MOR of only 1.052 MPa, indicating insufficient internal bonding. Addition of 5% PVOH markedly improved the MOR to 6.537 MPa. Further increase to 10% and 15% PVOH yielded MOR values of 9.822 MPa and 9.681 MPa, respectively. Notably, both the 10% and 15% formulations exceeded the ≥8 MPa requirement for Class 8 particleboard according to JIS A 5908, demonstrating that the 10% PVOH panels satisfy the minimum flexural performance standard for non-structural interior applications.

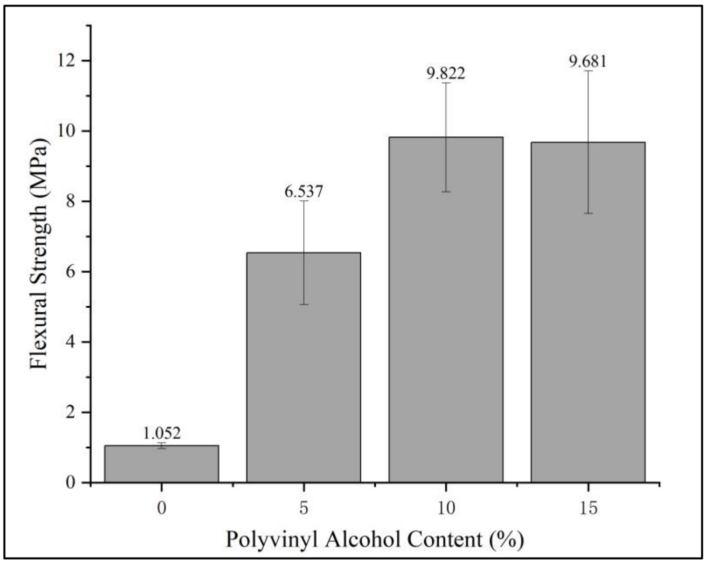

Figure 4. Flexural properties of biobased thermal insulation panels under different PVOH ratios

This improvement is attributed to enhanced interfacial bonding between rice husk fibers and the PVOH matrix through hydrogen bonding, which facilitates efficient stress transfer (Shakir et al., 2024). At 10% PVOH, optimal binder distribution and fiber-matrix interaction were achieved. However, at 15% PVOH, excess polymer led to localized plasticization and reduced stress transfer efficiency. Similar trends have been reported in PP–rice husk biocomposites, where controlled reinforcement improved flexural performance through stiffening and nucleation effects (Hidalgo-Salazar et al., 2019), and in PVA–rice husk ash nanocomposites, where low filler levels enhanced bending resistance via uniform dispersion (Sirait et al., 2023).

3.3.2. Tensile strength

The tensile strength of the biobased panels exhibited a non-monotonic dependence on PVOH content (Figure 5). At 5% PVOH, tensile strength reached 2.802 MPa. The maximum value of 4.369 MPa was obtained at 10% PVOH, representing a substantial improvement over the 5% formulation. Increasing the PVOH content further to 15% resulted in a decline to 3.721 MPa.

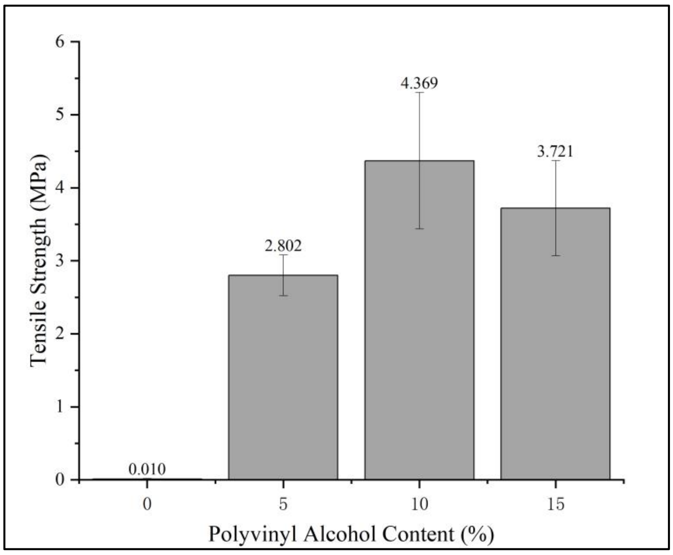

Figure 5. Tensile strength of biobased thermal insulation panels under different PVOH content

The reduction at higher PVOH loading is likely due to excessive polymer causing local stiffness imbalance, plasticization, or microvoid formation during curing, which impairs effective stress transfer. This behavior aligns with observations in rice husk–PP composites, where high filler loadings reduced ductility through agglomeration (Fayzullin et al., 2025), and in optimized rice husk/straw–epoxy systems, where an intermediate reinforcement level (around 8 wt%) yielded peak tensile performance due to improved interfacial compatibility (Ghalme, 2021). Overall, the 10% PVOH formulation provided the best balance between reinforcement efficiency and matrix homogeneity.

3.3.3. Internal bond strength

The internal bond (IB) strength increased significantly with PVOH addition (Figure 6). The 0% PVOH control showed extremely low cohesion (0.001 MPa). Introduction of 5% PVOH raised IB strength to 0.030 MPa, while the highest value of 0.038 MPa was achieved at 10% PVOH. At 15% PVOH, IB strength decreased to 0.025 MPa.

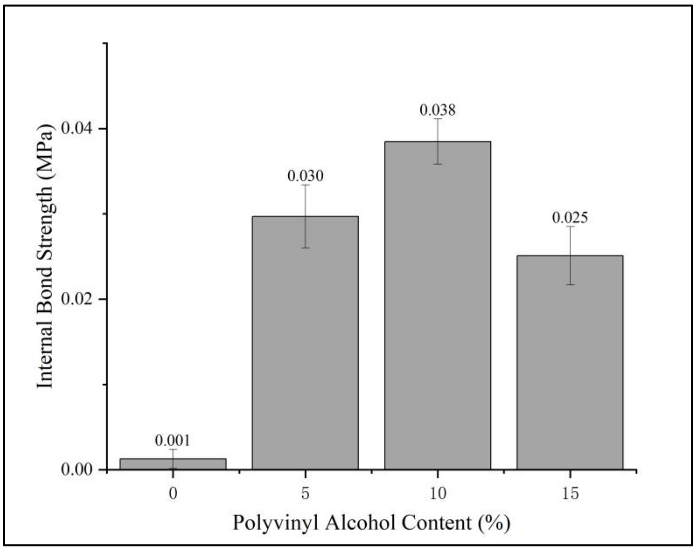

Figure 6. Internal bond strength of biobased thermal insulation panels under different PVOH ratios

This trend reflects improved fiber–matrix adhesion and more effective penetration of PVOH into the fiber network at the optimal loading. The decline at 15% PVOH may result from uneven curing and reduced porosity for mechanical interlocking caused by excess polymer. These results are consistent with the mechanical performance trends observed in flexural and tensile tests, confirming that 10% PVOH provides the best overall fiber–matrix interaction and structural integrity.

Collectively, the mechanical test results indicate that 10% PVOH represents the optimal binder content, delivering the best balance of flexural strength, tensile strength, and internal bond strength while meeting relevant particleboard standards.

3.4. Thermal Conductivity

The thermal conductivity (k) of the rice husk–polyvinyl alcohol (RH–PVOH) biobased thermal insulation panels was determined using the transient plane source (TPS) method at the optimal formulation of 10% PVOH, selected based on superior mechanical strength, moisture resistance, and dimensional stability from prior evaluations. Table 1 summarizes the key thermal properties measured for this composition.

Table 1. The thermal conductivity and thermal resistance of the thermal insulation panel of RH fibers under the optimal ratio (10%PVOH)

Material	Density (kg/m³)	Thermal conductivity	Reference
Rice husk + 10% PVOH (this study)	800	0.245	Current study
Rice husk + PBAT/PLA	378	0.08	(Muthuraj et al., 2019)
Ground rice husk + natural rubber foam	/	0.086	(Tuampoemsab et al., 2023)
Rice husk + sodium silicate	250–450	0.061–0.098	(Cigarruista Solís et al., 2024a)

The measured thermal conductivity of 0.245 W/m·K demonstrates that the RH-PVOH biobased panel exhibits promising thermal insulation capability for a lignocellulosic based material. This relatively low thermal conductivity can be primarily attributed to the porous microstructure of rice husk particles, which facilitates the entrapment of still air within the composite matrix. Since air has a very low thermal conductivity of approximately 0.026 W/m·K, the presence of internal pores and void spaces within the composite structure significantly restricts heat transfer through the material (Muthuraj et al., 2019). Furthermore, the incorporation of PVOH contributes to the formation of a continuous polymer matrix that enhances fiber matrix bonding while limiting direct solid phase heat conduction paths across the composite panel (Cigarruista Solís et al., 2024b).

The thermal behavior of the composite is also strongly influenced by its density and internal structure. In this study, the composite panels were fabricated at a target density of approximately 800 kg/m³, which is relatively higher than many lightweight bio-insulation materials. Generally, higher-density composites tend to exhibit increased thermal conductivity because of the larger proportion of solid material available for heat transfer (Tupciauskas et al., 2023). However, the RH–PVOH biobased panel maintained a relatively moderate thermal conductivity value, suggesting that the porous morphology of rice husk particles and the homogeneous dispersion of PVOH effectively preserved internal air pockets that impede heat conduction.

Comparison with previous studies further highlights the thermal performance of the developed composite. Muthuraj et al. (2019) reported a significantly lower thermal conductivity of 0.08 W/m·K for rice husk composites bonded with PBAT/PLA binder at a density of 378 kg/m³, where the lower density and increased porosity contributed to enhanced insulation properties (Muthuraj et al., 2019). Similarly, Tuampoemsab et al. (2023) measured a thermal conductivity of 0.0862 W/m·K in natural rubber foam reinforced with ground rice husk. In addition, rice husk insulation panels bonded with sodium silicate and other binders have been reported to exhibit thermal conductivities in the range of 0.061–0.098 W/m·K depending on density, binder composition, and processing conditions (Tuampoemsab et al., 2023). The higher thermal conductivity observed in the present study can therefore be reasonably attributed to the comparatively higher density and the non-foamed structure of the RH–PVOH composite panels.

Nevertheless, the obtained thermal conductivity value remains within the typical range reported for lignocellulosic insulation composites used in building materials. Importantly, the incorporation of PVOH provides improved mechanical integrity and structural stability of the composite panel without excessively increasing thermal conductivity. This balance between mechanical strength and thermal insulation performance is particularly important for building insulation applications, where materials are required not only to reduce heat transfer but also to maintain sufficient durability and dimensional stability under service conditions. It is noteworthy that thermal conductivity measurements were conducted on the 10% PVOH sample, which demonstrated the optimal overall mechanical performance and dimensional stability. This approach aligns with common practices in biobased panel optimization research, where in-depth thermal characterization is prioritized for the most promising formulations. Future work will encompass thermal conductivity measurements across all PVOH ratios to enable a more comprehensive comparison.

4. Discussion

This study developed a rice husk fiber-based biobased thermal insulation panel using polyvinyl alcohol as a sustainable, water-soluble binder for thermal insulation in energy-efficient building envelopes. Through systematic optimization of PVOH content (0–15 wt%), the formulation containing 10 wt% PVOH delivered the optimal balance of mechanical performance, dimensional stability, and thermal insulation efficacy. The optimized biobased panel achieved a flexural strength of 9.82 MPa, a tensile strength of 4.37 MPa, and an internal bond strength of 0.038 MPa, meeting the minimum requirements of JIS A 5908 Class 8 for particleboard used in non-structural interior applications. Dimensional stability was confirmed by moderate water absorption (92.13%) and thickness swelling (33.61%), values indicative of effective interfacial adhesion between rice husk particles and the PVOH matrix attributable to hydrogen bonding between PVOH hydroxyl groups and cellulose/hemicellulose surface functionalities (Shakir et al., 2025a). Although the water absorption and thickness swelling of the 10% PVOH formulation are relatively high compared with conventional synthetic insulation materials, these values are typical for untreated lignocellulosic biocomposites. For practical application in building envelopes especially under humid conditions the panels are recommended to be used with appropriate moisture protection, such as hydrophobic surface coatings or lamination with vapour-permeable membranes. Thermal characterization yielded a bulk thermal conductivity of 0.245 W/m·K, positioning the material competitively among bio-based insulation panels despite its higher density and underscoring the insulating contribution of rice husk's intrinsic silica network. This study demonstrates the feasibility of utilizing rice husk agricultural waste combined with a biodegradable PVOH binder to produce a sustainable, bio-based insulation material. By valorizing agricultural residues into functional building materials, the proposed biobased thermal insulation panel contributes to the development of low-carbon and resource-efficient insulation solutions that support circular economy principles in sustainable building construction (Shakir et al., 2017).

Several limitations of the present study should be acknowledged. The chemical composition and silica content of rice husk can vary with rice variety, milling conditions, and geographical source, potentially affecting reproducibility. In addition, the hygroscopic nature of lignocellulosic fibers means that ambient humidity during fiber storage and sample conditioning could influence water absorption and thickness swelling results. Although steps were taken to minimize these effects including sourcing all rice husk from a single batch and using four to five replicates per test larger sample sizes and multi-batch experiments would strengthen statistical robustness. Future work will include thermal conductivity measurements across all PVOH ratios and explore surface treatments to further improve moisture resistance.

Meanwhile, although existing studies have demonstrated that natural fiber biocomposites generally feature lower embodied carbon emissions and superior end-of-life cycle sustainability compared with petroleum-based foam materials (Ahmad et al., 2022), this study has not conducted a comprehensive life cycle assessment (LCA) of the current RH–PVOH formulation, including detailed cradle-to-gate embodied energy calculation and scenario analysis of post-disposal treatment. It is recommended that future studies incorporate a complete life cycle assessment to quantify the exact carbon footprint reduction potential of this formulation.

Author Contributions

For research articles with several authors, we encouraged authors to provide a short paragraph to state the their individual contributions, e.g., Conceptualization, Z.J. and M.A.S.; methodology, Z.J.; validation, L.M., A.A.A. and M.I.A.; formal analysis, M.A.S.; investigation, M.I.A.; resources, M.I.A.; data curation, Z.J.; writing—original draft preparation, Z.J.; writing—review and editing, M.I.A.; visualization, M.I.A.; supervision, M.I.A.; project administration, M.I.A.; funding acquisition, M.I.A. All authors have read and agreed to the published version of the manuscript. Authorship must be limited to those who have contributed substantially to the work reported.

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Conflict of Interest Statement

Author declares no conflict of interest.

Data Availability Statement
Data is unavailable due to privacy or ethical restrictions.

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