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Characterization of eco-friendly polyurethane foam composites with bagasse and rice husk waste for thermal insulation applications

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ABSTRACT

Reducing the use of petrochemical-based polyurethane foams in thermal insulation applications is necessary to reduce environmental impacts. Natural fibers as fillers have emerged as promising ecological alternatives, promoting environmentally friendly and sustainable material practices. This study aimed to evaluate the mechanical and thermal properties of eco-friendly polyurethane foam composites containing bagasse fiber (BF) and rice husk (RH) waste. Rigid polyurethane foam (PUR) composites with BF and RH waste particles were prepared at different filler loading levels (20%, 30%, and 40%). Density, mechanical properties, thermal conductivity, thermal stability, and morphology of the composites were evaluated. The results showed that the density of the PUR composites with the BF and RH particles increased along with filler addition. Higher composite density led to increased thermal conductivity. The mechanical properties, bending strength, and bending modulus of the PUR composites with BF and RH were lower than those of pure PUR and decreased further with filler content. However, combining both fillers increased the mechanical properties by up to 172%. Thermal conductivity analysis indicated that thermal resistance decreases as filler content increases. However, the thermal conductivity values (0.0275–0.0393 W/mK) demonstrate competitive performance, comparable to conventional insulation materials, while supporting sustainability through waste utilization and reduced PUR consumption. This material shows strong potential as a thermal insulation solution for buildings and sustainable construction, particularly in the regions with abundant agricultural waste.

Keywords: bagasse waste, eco-friendly, rice husk waste, rigid polyurethane foam, thermal insulation.

INTRODUCTION

The use of insulation materials has significantly increased in energy-efficient building construction. In tropical climates with high temperatures and humidity, applying insulation to the building envelope is crucial for ensuring comfort and energy-efficiency. One of the most widely used synthetic insulation materials is rigid polyurethane foam (PUR) (Andersons et al., 2020; Raza et al., 2022). It has low density, a closed-cell structure, and low thermal conductivity (0.024–0.300 W/mK), making it highly effective for thermal insulation applications (Ahirwar et al., 2022; Pásztory, 2021). Polyurethane foam is produced through the reaction of polyols and isocyanates. It offers wide formulation flexibility, superior mechanical properties; in addition, it can be processed and molded using relatively simple methods (Wang et al., 2022). In 2020, the global demand for PU products increased to 22 million tons, with rigid PU foam as the most widely consumed type. However, approximately 15% of rigid PU foam produced was wasted (Abu-Jdayil et al., 2022). Furthermore, PUR production remains dependent on petrochemicals and generates a relatively high carbon footprint (Kausar, 2018), highlighting the need for innovative and environmentally friendly alternatives. This aligns with the global focus on sustainability and reducing environmental impact.

One promising strategy to reduce the PUR use in manufacturing environmentally friendly insulation materials is incorporating filler particles from agricultural waste. From an environmental perspective, lignocellulose-based agro-industrial waste is increasingly favored over synthetic fibers (Abu-Jdayil et al., 2019; Ayadi et al., 2023; Zhao et al., 2020). Lignocellulosic composites are biodegradable, abundant, low-cost, carbon-neutral, easy to process, and pose minimal health risks (Mawardi et al., 2023; Samanta et al., 2022). Citura et al. (Cintura et al., 2021) and Char et al. (Char et al., 2025) reviewed the potential of agro-industrial waste as building insulation materials. Ecological insulation materials based on natural fibers agglomerated with various adhesives can be manufactured from wood (Dukarska et al., 2022), date palm (Oushabi et al., 2017), rice straw and coconut husk (Simamora et al., 2023), oil palm wood (Mawardi et al., 2021), plant fiber (Char et al., 2025), wool and sugarcane bagasse (Beheshti et al., 2023), and Oil Palm Empty Fruit (OPEF) and bagasse (Ramlee et al., 2021), all of which show promising results as insulation materials.

Furthermore, previous researchers have studied the PUR-based natural fiber composites for building insulation, such as wood fiber (Choe et al., 2018), bamboo (Shao et al., 2020), hemp (Haghighatnia et al., 2017), and date palm (Oushabi et al., 2017). These composites were produced in panel/board form and evaluated. Results showed that these natural fibers have good thermal insulation properties and can be applied to buildings. Otto et al. (Otto et al., 2017) studied PU composites by replacing up to 20% w/w of polyethylene glycol in conventional polyurethane foam with a mixture of one of three natural fibers: bagasse, sisal, and rice husk. The resulting hybrid composites had resilience of up to 32 percent, an elastic modulus of 0.1 GPa, and permanent deformation of 7.32%. Sair et al. (Sair et al., 2018) reported the mechanical and thermal conductivity properties of hemp fiber-reinforced polyurethane composites. The PUR composites were prepared with hemp fiber loadings of 5%, 10%, 15%, 20%, 25%, and 30%. The results show that the composite with 15% wt fiber loading achieved a 40% increase in strength, and thermal conductivity increased linearly with density.

Agro-industrial waste, such as bagasse fiber (BF) and rice husk (RH) have great potential as PUR composite fillers for ecological insulation materials. BF contains cellulose, hemicellulose, and lignin, while RH is rich in silica, making both suitable for insulation materials (Amaresh et al., 2024; Amran et al., 2021; Kusuma et al., 2023; Pérez et al., 2025). BF and RH are abundantly available in tropical countries, such as Indonesia. In 2024, Indonesian sugarcane plantations covered 524,886 ha with a production of 2.46 million tons (Directorate General of Estates, Ministry of Agriculture, 2024), of which 30–40% of the sugarcane weight produces bagasse waste (Long et al., 2025). Similarly, the rice husk potential was high: the Central Statistics Agency recorded 7.38 million ha of rice fields with a production of 53.98 million tons in 2024 (Directorate General of Estates, 2024). Furthermore, Sulaiman reported that approximately 120 million tons of rice husks are produced annually, but only a small portion is effectively utilized. Utilizing this waste reduces environmental impact and increases the added value of insulation materials tailored to application needs (Sulaiman, 2025).

Although extensive research has been conducted on polyurethane (PU) foam and organic waste fillers, there is a lack of comprehensive studies on the thermal and mechanical properties of the PU foam composites reinforced with bagasse and rice husk particles, either individually or in hybrid form. In particular, the effects of filler composition and hybridization on mechanical strength and thermal resistance have not been systematically explored. A critical review of existing literature reveals no prior work specifically addressing using bagasse and rice husk particles as reinforcement for rigid PU foams in thermal insulation applications. To bridge this gap, the present study developed an eco-friendly thermal insulation material based on the PU composites filled with bagasse and rice husk waste. The composites were fabricated with varying filler compositions (bagasse fiber, rice husk, and their hybrid), and the influence of filler content on PU weight fraction was investigated. Key properties including density, bending strength, thermal conductivity, and filler–matrix morphology were systematically characterized. The findings demonstrate that these green composites reduce PU consumption and contribute to mitigating agro-industrial waste in Indonesia.

MATERIALS AND METHODS

Materials

This study used two materials to develop sustainable thermal insulation: bagasse waste and rice husk. BF, a residue from the sugarcane milling process (sugarcane juice), was collected in Lhokseumawe, Aceh, Indonesia, in the form of long, crushed pieces. RH was collected from a local rice milling factory in North Aceh district, Aceh, Indonesia. The composite matrix used rigid polyurethane foam (PUR) with a density range of 50–260 kg/m^3, supplied by Pancamuda Perkasa Corp in Jakarta, Indonesia. PUR resin consists of two components: component A (polyol) and component B (isocyanate), which were mixed in equal volume proportions. The characteristics of bagasse fiber, rice husk, and rigid polyurethane foam are shown in Table 1.

Extraction and pretreatment of bagasse and rice husk

Bagasse fiber and rice husk waste underwent the same pretreatment process. First, the bagasse was manually cut into small pieces approximately 20 to 30 mm long. Both bagasse and rice husk flakes were soaked in a 5% NaOH solution for 4 hours. After soaking, they were washed with water to neutralize the NaOH solution and sun-dried for 3 to 5 days, depending on weather conditions, to reduce moisture content. Finally, the flakes were ground into particles using a disc mill (Model FFC-23, Agrowindo, Indonesia) until they passed through a 40-mesh sieve. The extraction and pretreatment process are illustrated in Figure 1.

PUR composites production process

The production of the PUR composite samples with the BF and RH particle fillers followed the manufacturer's instructions (Figure 2), using the formulation shown in Table 2. First, both particles were dried in an electric oven (Model Yatt-400, Indonesia) at 80 °C for 1 hour to reduce the moisture content to below 10%. The particles and polyol were then mixed in a container and stirred mechanically (Model HM-620, Miyako, Indonesia) at 200 rpm for 5 minutes until homogenous. Furthermore, the mixture was poured into a closed mold (400 × 400 × 20 mm), after which isocyanate was added, stirred quickly until fully mixed, and the mold was closed. The PUR composite mixture expanded freely in the vertical dimension. The ratio of polyol (component A) and isocyanate (component B) the ratio is equal. Within 5–10 minutes, the foam composite hardened and was conditioned at room temperature for at least 2 days before characterization.

Characterization procedure

Bending strength test

Three-point bending tests were performed on the PUR composite specimens. Test samples with dimensions of 150 × 20 × 20 mm were prepared and tested based on ASTM D790 standard (D.-03 ASTM, 2003). Five specimens were prepared and validated for each composite type. Testing was conducted using a Universal Testing Machine (TE, WDW-105 Model, China) with a 10 kN capacity, as shown in Figure 3, at a crosshead speed

Table 1. Characteristics of BF, RH, and PUR (Ali et al., 2024; Almusaed and Almssad, 2016; Ramlee et al., 2021; Singh et al., 2023)

Description	Bagasse fiber	Rice husk	PUR
Physical and mechanical			
Density (kg/m^3)	400–550	900–1800	50–260
Tensile strength (MPa)	20–290	28–134	26.50–55.20
Young's modulus (GPa)	19.70–27.10	0.90–2.60	2.20–2.62
Chemical constituents (%)			
Cellulose	25.00–55.20	35–50	-
Hemicellulose	16.80–25.00	7–22	-
Lignin	21.00–25.30	19–30	-

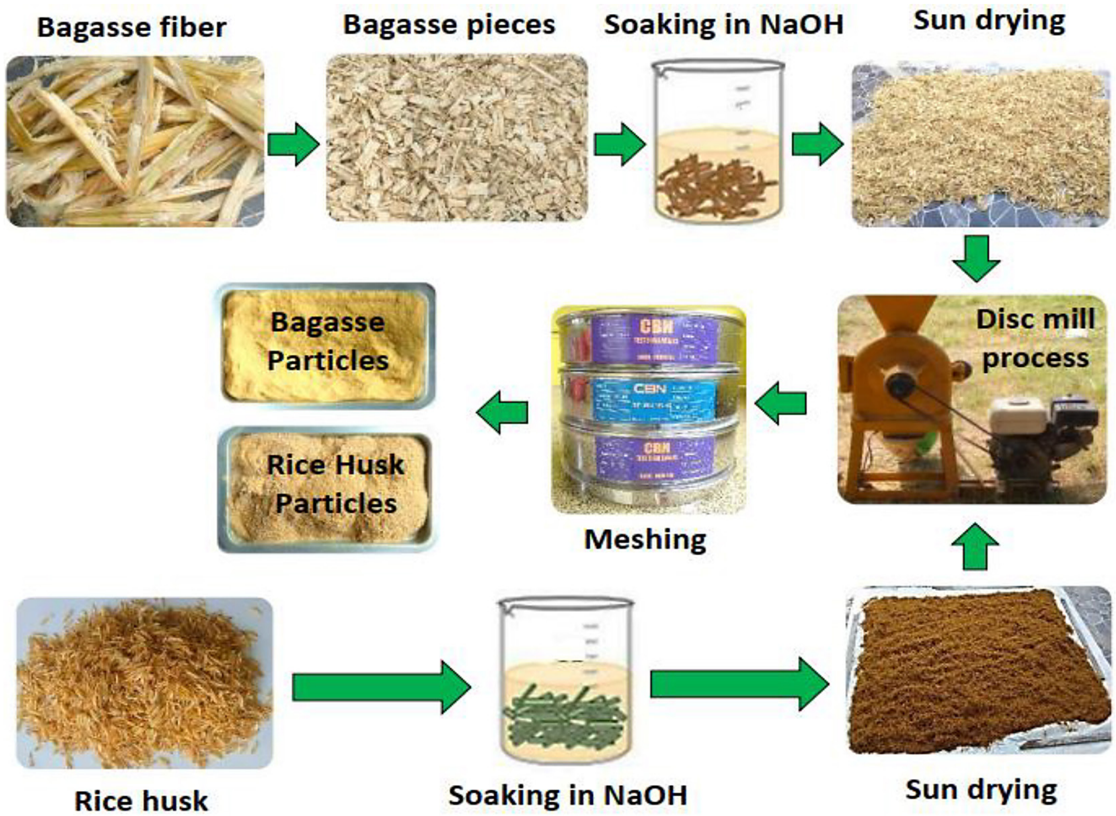

Figure 1. Extraction and pretreatment process of BF and RH

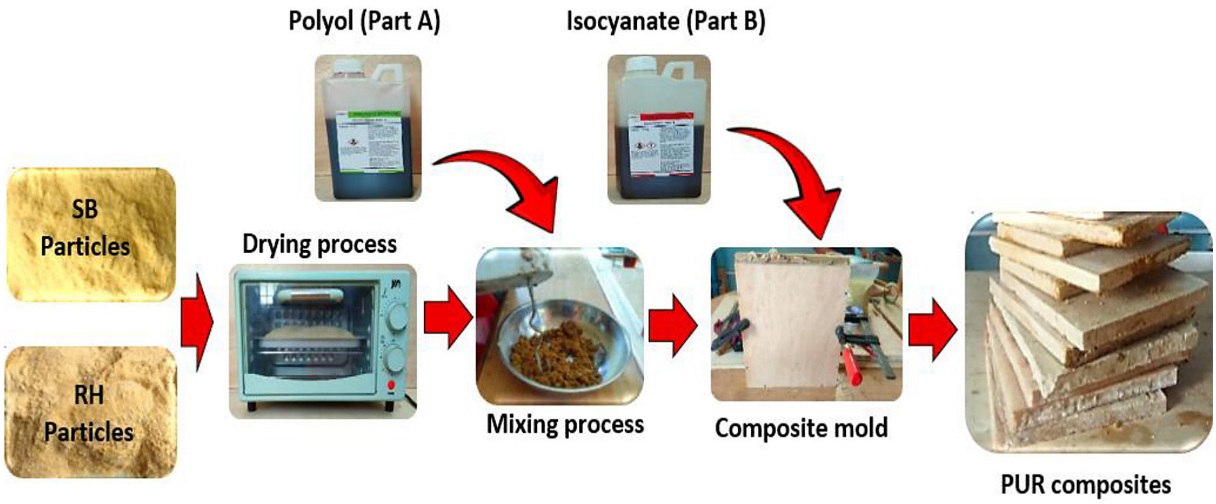

Figure 2. Process of production of the PUR composite filled with the BF/RH particles

of 2 mm/min. All tests were conducted under controlled room conditions at 25 °C and 60% relative humidity. During testing, the force (F), deflection (y), and bending stress (σ_f) parameters were recorded. Bending strength and elastic modulus were calculated using Equations 1 and 2, where L, b, and b represent the span length, thickness, and width of the specimen, respectively, and y is the gradient obtained from the force–deflection curve.

Thermal conductivity test

Thermal conductivity testing was conducted using an insulated box (PHYWE SYSTEME GMBH 37070 Göttingen, Germany), with a central heating element as the heat source (Figure 4). The test followed ASTM C177-97 (C.-97 ASTM, 1997). Five specimens, each 200 mm x 200 mm, a PUR composite sample, were prepared and

Table 2. The PUR composite formulation is filled with the BF/RH particles

Composite sample	PUR (wt%)	BF (wt%)	RH (wt%)
PU	100	0	0
PUBF2	80	20	0
PUBF3	70	30	0
PUBF4	60	40	0
PURH2	80	0	20
PURH3	70	0	30
PURH4	60	0	40
P8BFRH	80	10	10
P7BFRH	70	15	15
P6BFRH	60	20	20

installed on one wall of the insulated box, which was perforated to match the sample size. The thermal conductivity measurement involved four Type K thermocouple sensor probes installed inside and outside the box: one inside the box to measure the temperature, one on the inner wall of the sample, and two outside—on the outer wall of the sample and outside the box. The probes were connected to a four-channel HT9815 thermocouple thermometer to record the measured temperature.

The thermal conductivity test began by turning on the heat source until the temperature inside the box reached 60 °C, which was maintained for 30 minutes to achieve a steady state. Four

Figure 3. PUR composite with BF/RH particles bending specimen

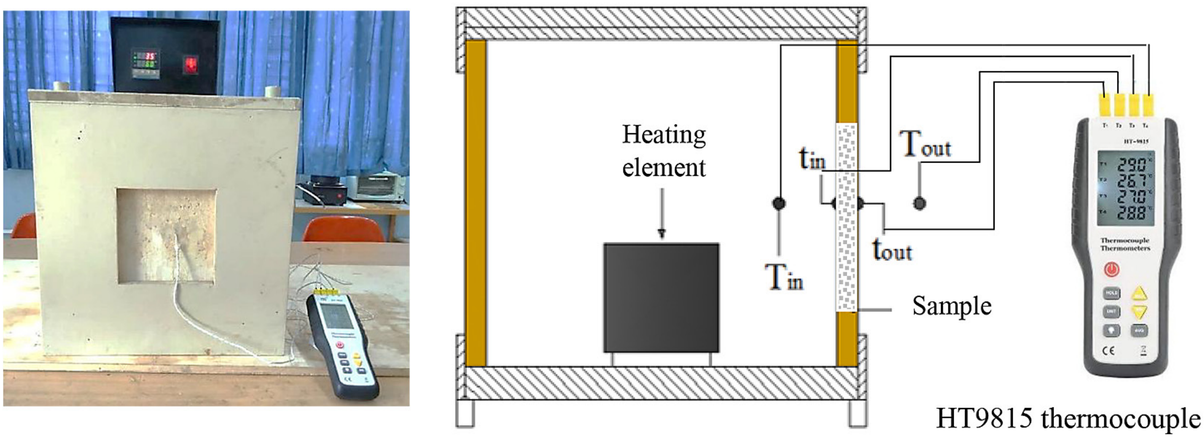

Figure 4. Insulation box for measuring the thermal conductivity of PUR composites

temperature measurements were recorded: the temperature inside the box, the temperature of the inner wall of the specimen, the temperature of the outer wall of the specimen, and the room temperature. The thermal conductivity of the PUR composite filled with BF and RH was calculated using Equation 1 (Limam et al., 2016).

$$Q_{c,wall} = -kA\frac{T_1 - T_2}{\Delta x}\ (W) \quad (1)$$

where: T_1 is the inner surface temperature, T_2 is the outside surface temperature, Δx is the distance between the two surfaces, and A is the wall surface.

Scanning electron microscopy

Scanning electron microscopy (SEM) images of the PUR composite-filled BF and RH were obtained using a Zeiss Evo 15 scanning electron microscopy (Germany). Prior to analysis, the samples were coated with gold using a MiniQS Quorum. The surface of the PUR composite-filled BF and RH samples was observed using scanning electron microscopy at an accelerating voltage of 5 kV.

RESULTS AND DISCUSSION

Bending properties

Figure 5 presents the bending strength-displacement curves for the BF and RH-filled PUR composites. The curves indicate that the composite operates in the non-linear elastic region, a common phenomenon in composites due to complex interactions between the reinforcement matrix, load transfer mechanisms, and microstructural characteristics. Beyond the elastic limit, the curves exhibit non-linear behavior, indicating the onset of matrix cracking, fiber-matrix bond release, and fiber pullout mechanisms (AhmadvashAghbash et al., 2023).

Figure 6 shows the bending strength and modulus graphs of the PUR composites filled with the BF and RH particles, with pure PUR samples used as controls. The bending strength of the PUR composites filled with the BF particles ranged from 0.35 to 0.51 MPa, those filled with the RH particles ranged from 0.22 to 0.38 MPa, whereas the composites filled with BF and RH ranged from 0.44 to 0.60 MPa. The highest bending strength was observed at 20% filler loading, (samples PUBF2 and PURH2). In this case, adding the BF and RH particles as fillers caused a decrease in bending strength. These results align with previous tests on the PUR composites filled with sawdust conducted by (Dukarska et al., 2022), where 20% sawdust in PUR produced a lower bending strength, compared to 5%, 10%, and 15%.

Increasing filler content and reducing the matrix volume gradually decreased bending strength. A higher proportion of the BF and RH particles compared to the PUR matrix weakened the matrix-filler interface, ultimately reducing the bending characteristics of the composite. SEM images supported these findings, revealing

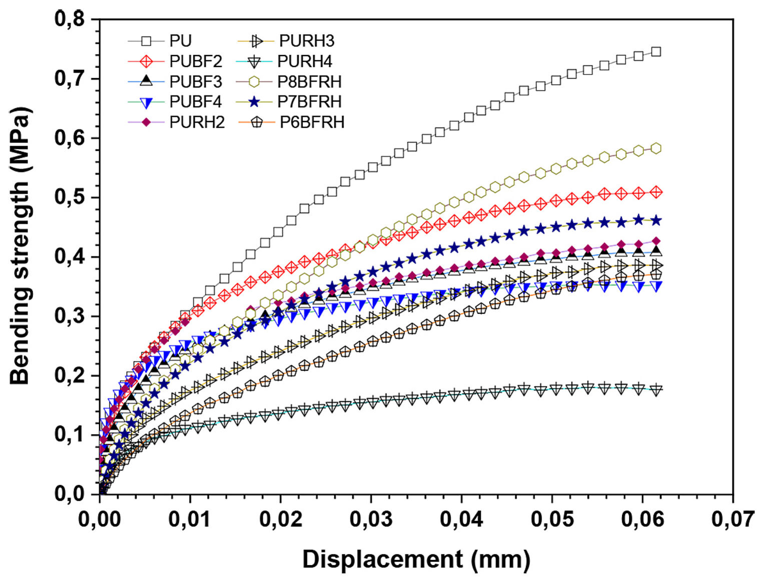

Figure 5. Bending strength vs displacement curve of the PUR composites filled with BF and RH

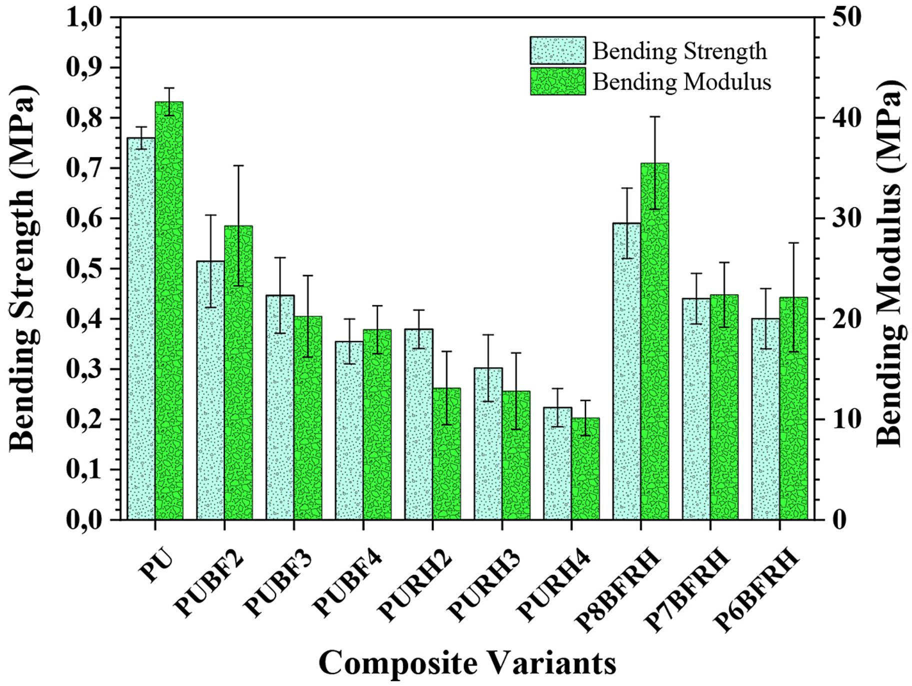

Figure 6. Bending strength and modulus of the PUR composites filled BF and RH

agglomeration, gaps between fillers, inadequate adhesion, and reduced load-path continuity. These defects were more pronounced at higher filler contents, reducing mechanical performance and limiting moldability. The expanding PUR matrix could not effectively disperse and bind the filler, resulting in filler accumulation and stress concentration centers.

Furthermore, the findings revealed that hybridizing the BF with RH particles increased bending strength by up to 172%. This demonstrates that combining fillers in specific ratios can optimize structural integrity under bending, allowing the composite to withstand heavier loads before failure.

Bending modulus

Figure 6 shows the bending modulus of the PUR composites filled with the BF and RH particles, representing material stiffness under bending. The modulus trends similarly to bending strength: increasing the filler-to-PUR matrix ratio generally reduces the overall modulus. However, the composites with lower filler content maintain an acceptable modulus while benefiting from reduced density. This trade-off between stiffness and weight underscores the importance of optimizing the filler content. Similar findings were reported by (Sair et al., 2018), showing that adding moderate amounts of ramie fiber increased the modulus without compromising structural performance. The bending modulus of the PUR composites ranged from 10.13 MPa to 35.50 MPa. The highest bending modulus was observed in the sample with a 20% combined BF/RH filler (P8BFRH), and the lowest modulus values in the sample with 40% combined BF/RH filler (PURH4). These findings confirm that combining the BF and RH particle fillers significantly outperforms individual fillers.

The BF and RH-filled PUR composites exhibit a good combination of stiffness, strength, and bending ductility at the optimal filler-to-matrix ratio. The hybridization strategy exploits the strong synergistic effect between the reinforcing phases when properly balanced. This balance is an important factor in future applications of thermal insulation materials.

Thermal conductivity, thermal resistance, and density

In thermal insulation materials, the most important property and often the primary parameter considered is thermal conductivity, which affects heat flow mechanism and temperature distribution under fixed heat transfer conditions. The thermal conductivity properties of PUR composites reinforced with BF and RH particles were analyzed to evaluate their effectiveness in controlling heat transfer. In buildings, thermal conductivity is an important parameter for thermal insulation materials used in heat-demanding environments such as roofing, walls, and other protective panels. The effects of the BF and RH fillers on thermal conductivity, thermal resistance, and their relationship to PUR composite density are shown in Figure 7.

The PU control sample without BF and RH fillers showed the lowest thermal conductivity, 0.0262 W/mK, primarily due to the PUR structure forming pores after swelling. SEM image shows the honeycomb-like microstructure of pure PUR, which contains many pores. These air-filled pores act as effective barriers for phonon transport, enhancing the insulator. Adding the BF and RH particles to the PUR composites increased thermal conductivity by up to 50% compared to unmodified PUR. This significant increase is attributed to the high intrinsic thermal conductivity of the BF and RH particles, which form thermally conductive paths within the PUR matrix. This finding is supported by comparisons with reported values: PUR (0.0250–0.0301 W/mK) (Pásztory, 2021) exhibits lower thermal conductivity than bagasse (0.0460–0.0490 W/mK) and rice husk (0.0464–0.5660 W/mK) (Schiavoni et al., 2016).

Figure 7 shows that thermal conductivity increases with both density and filler content. Although filler addition slightly raises thermal conductivity, the PUBF2 composite, containing 20% BF particles, showed the lowest value (0.0275 W/mK) among the tested BF and RH filled PUR composites. In contrast, the P5BFRH sample, with 40% combined BF and RH particles, had the highest thermal conductivity (0.0393 W/mK). This is due to its dense microstructure, high density, and the characteristics of the filler, which reduces thermal resistance.

The PUR composites filled with the BF particles show thermal conductivity ranging from 0.0275–0.0316 W/mK, with thermal resistance of 0.6333–0.7270 m^2K/W. Meanwhile, the PUR composites filled with the RH particles show higher thermal conductivity, ranging from 0.0322–0.0356 W/mK, with thermal resistance of 0.5816–0.6523 m^2K/W. Furthermore, the PUR composites filled with a combination of BF and RH produce thermal conductivity in the range of 0.0366–0.0393 W/mK. This increase is likely due to the formation of more efficient thermal bridges, resulting from the closer proximity of particles and higher density, which facilitates phonon hopping and reduces thermal resistance.

In general, the thermal conductivity of the PUR composites filled with the BF and RH particles correlates with density, increasing proportionally as density rises. This finding is supported by previous studies (Ali et al., 2025; Sair et al., 2018). The particles fill micro-voids and compact the composite, reducing thermal resistance. This behavior is expected, as this study aimed to obtain a composite with the insulating properties close to commercial insulation, while maintaining cost efficiency and reducing the environmental impact of petroleum-based materials. At higher particle concentrations, agglomeration is more likely due to limited compatibility and limited

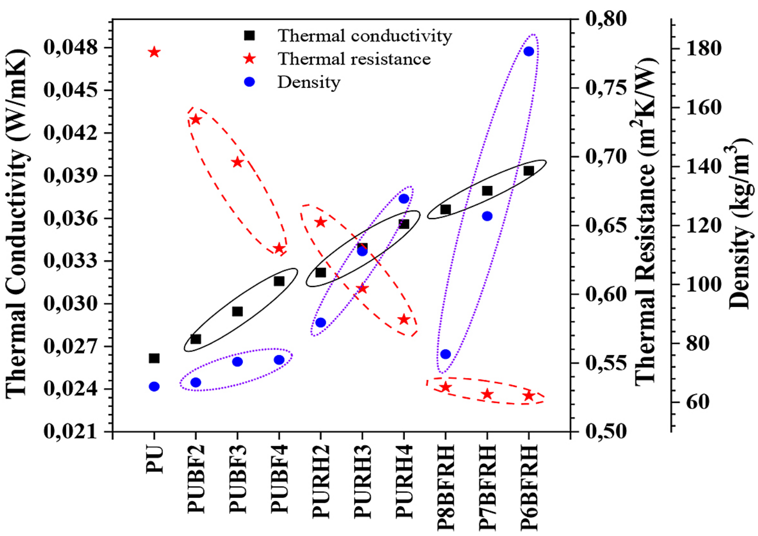

Figure 7. The relationship between thermal conductivity, thermal resistance, and density of the PUR composites filled with BF and RH particles

PUR expansion. Agglomeration reduces uniform particle dispersion and creates interface defects, inhibiting thermal conduction. Furthermore, thermal conductivity is inversely proportional to thermal resistance, with lower thermal conductivity values increasing thermal resistance.

Overall, the PUR composites filled with the BF and RH particles exhibit low thermal conductivity, ranging from 0.0275 to 0.0356 W/mK. This finding is better than that of the PUR composites reinforced with flax fiber (0.0339–0.0480 W/mK) (Sair et al., 2018) and the PUR filled with date palm (0.0344–0.0389 W/mK) (Oushabi et al., 2017). The PUR composites filled with the BF and RH particles show excellent thermal insulation properties, making them suitable for building applications requiring thermal conductivity below 0.0700 W/mK (Schiavoni et al., 2016).

Thermal conductivity, density, and bending strength

Figure 8 depicts the relationship between thermal conductivity, density, and bending strength of the PUR composites filled with BF and RH. Results indicate that increasing the density of polyurethane composites is associated with increased thermal conductivity. The pure PU sample with low density (65.35 kg/m³) had the lowest thermal conductivity (0.0262 W/mK), while higher densities samples, such as P6BFRH (179.06 kg/m³), showed an increase to 0.0393 W/mK. This indicates that adding filler particles increases matrix density, thus creating more effective heat transfer pathways.

However, the opposite trend was observed for bending mechanical properties. Bending strength decreased with increasing density and thermal conductivity. In this study, pure PU exhibited a bending strength of 0.76 MPa, which gradually decreased with increasing filler load, reaching 0.22 MPa for the PURH4 sample (density 129.07 kg/m³, conductivity 0.0356 W/mK). This condition confirms that although high density increases thermal conductivity, particle agglomeration and interface defects reduce the ability of the material to withstand bending loads. Overall, these three parameters show a trade-off between increasing density, which supports thermal conductivity, and decreasing bending strength. This trade-off is important when selecting the PUR composite formulations based on the BF and RH particles for thermal insulation and structural applications.

SEM micrographs

In this study, a scanning electron microscope was used to study the effect of BF and RH on the morphology of the PUR composites. Figure 9 shows micrographs of (A) pure PUR, (B) BF-filled PUR composite, (C) RH-filled PUR composite, and (D) BF and RH-filled PUR composite. Figure 9A shows the SEM image of the pure PUR structure, revealing closed, spherical cavities that are relatively uniform, each completely enclosed by

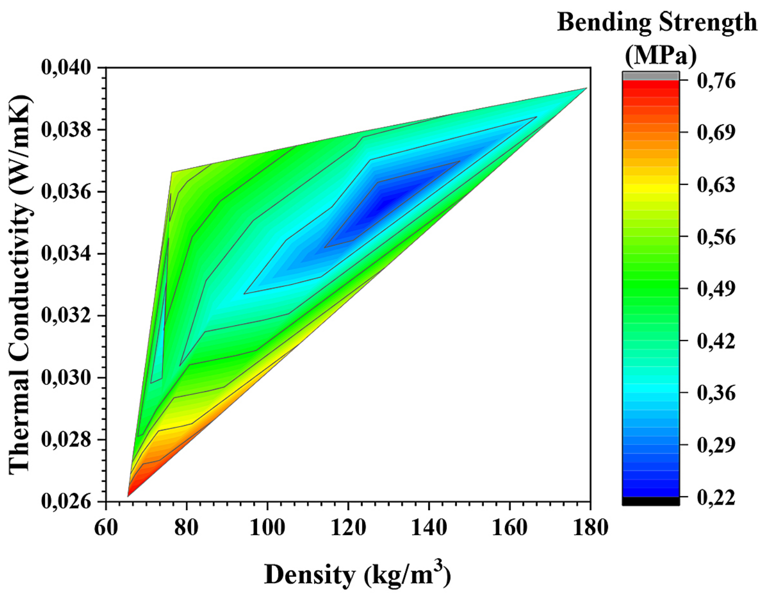

Figure 8. The relationship between thermal conductivity, density, and bending strength of th PUR composites filled with the BF and RH particles

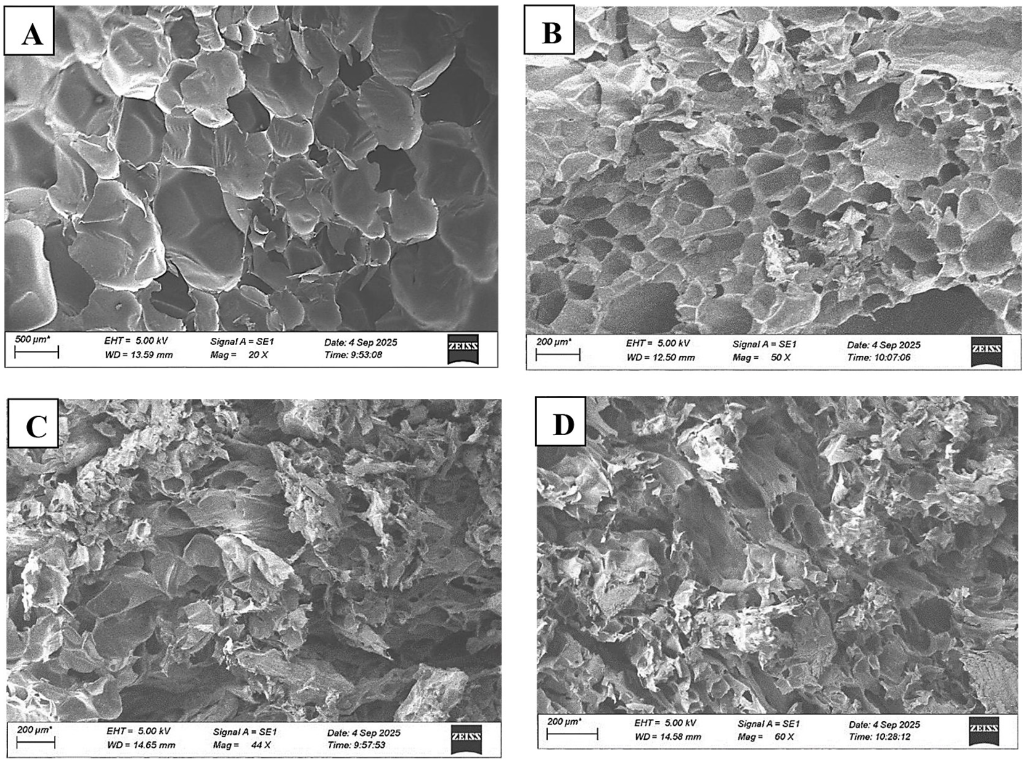

Figure 9. SEM micrographs of the pure PUR and PUR composites filled with BF and RH

a thin film. Similar observations were reported by (Kausar, 2018). Air-filled cavities and discontinuities in particle paths increase thermal resistance, thus impeding heat flow (Oushabi et al., 2017).

Figures 9B to 9D shows that the BF and RH particles disrupt the foam structure by damaging cell morphology, reducing foam quality. Increasing the BF and RH filler content results in particle agglomeration in certain areas of the PUR matrix, which can damage the foam structure. This phenomenon is primarily due to the natural hydrophilic nature of BF and RH, which is incompatible with the hydrophobic PUR matrix, encouraging particle aggregation. Furthermore, BF and RH dispersion is not optimal, resulting in uneven reinforcement distribution within the PUR matrix. Consequently, the matrix is damaged, and the foam loses its polyhedral morphology (Lazo et al., 2023).

These SEM results are consistent with bending test results, which showed decreased strength and toughness in samples with high agglomeration. Agglomerates act as stress concentrators, accelerating crack initiation and explaining the lower bending strength compared to the samples with good dispersion. Furthermore, contact between overlapping particles can form a particle network that acts as a thermal pathway, increasing the thermal conductivity of the composite.

CONCLUSIONS

This study demonstrated that the rigid polyurethane (PUR) composites reinforced with bagasse fiber (BF) and rice husk (RH) waste exhibit competitive thermal insulation performance while reducing reliance on petrochemical-based PUR. Increasing the filler content raised density and thermal conductivity but reduced bending strength due to weaker filler–matrix adhesion. Notably, combining BF and RH improved mechanical performance by up to 172%, highlighting the benefits of combining agro-waste fillers. Overall, the BF–RH reinforced PUR composites offer a sustainable alternative for thermal insulation in buildings, particularly in regions with abundant agricultural residues. These eco-friendly materials reduce PU consumption and contribute to waste valorization, supporting greener construction practices. While this study confirms the potential of bagasse and rice husk waste as fillers for eco-friendly PUR composites, several limitations should be noted. The reduced bending strength at higher filler loadings indicates the need for improved filler–matrix compatibility. Future research should explore surface modification of fibers, alternative coupling agents, or chemical treatments to enhance adhesion and mechanical performance.

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REFERENCES

1. Abu-Jdayil, B., Al Abdallah, H., Mlhem, A., Alkhatib, S., El Sayah, A., Hussein, H., Althabahi, A., AlAydaroos, A. (2022). Utilization of polyurethane foam dust in development of thermal insulation composite. *Buildings*, *12*(2), 126.
2. Abu-Jdayil, B., Mourad, A.-H., Hittini, W., Hassan, M., Hameedi, S. (2019). Traditional, state-of-the-art and renewable thermal building insulation materials: An overview. *Construction and Building Materials*, *214*, 709–735. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2019.04.102
3. Ahirwar, D., Telang, A., Purohit, R., Namdev, A. (2022). A short review on polyurethane polymer composite. *Materials Today: Proceedings*, *62*, 3804–3810.
4. AhmadvashAghbash, S., Verpoest, I., Swolfs, Y., Mehdikhani, M. (2023). Methods and models for fibre–matrix interface characterisation in fibre-reinforced polymers: a review. *International Materials Reviews*, *68*(8), 1245–1319.
5. Ali, H., Dixit, S., Alarifi, S. (2024). Development and characterization study of bagasse with stubble reinforced polyester hybrid composite. *Journal of King Saud University-Science*, *36*(7), 103231.
6. Ali, M., Almuzaiqer, R., Alshehri, H., Alanazi, M. A., Almudhhi, T., Nuhait, A. (2025). New bound and hybrid composite insulation materials from waste wheat straw fibers and discarded tea bags. *Buildings*, *15*(14), 2402.
7. Almusaed, A., Almssad, A. (2016). *Insulation materials in context of sustainability*. BoD–Books on Demand.
8. Amaresh, Nunavath, A., Vinayaka, Kumari, S., Avinash, G., Abhishek, G. J., Dhanya, V. G., Maruthi, R. T., Krishnappa, G., Swamy, H. K. M. (2024). Sugarcane bagasse: Transforming waste into renewable and bio-compostable materials for a sustainable future. In *Value addition and product diversification in sugarcane* 239–256. Springer.
9. Amran, M., Fediuk, R., Murali, G., Vatin, N., Karelina, M., Ozbakkaloglu, T., Krishna, R. S., Sahoo, A. K., Das, S. K., Mishra, J. (2021). Rice husk ash-based concrete composites: A critical review of their properties and applications. *Crystals*, *11*(2), 168.
10. Andersons, J., Kirpluks, M., Cabulis, U. (2020). Reinforcement efficiency of cellulose microfibers for the tensile stiffness and strength of rigid low-density polyurethane foams. *Materials*, *13*(12), 2725.
11. ASTM, C.-97. (1997). *Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus*. American Society for Testing and Materials.
12. ASTM, D.-03. (2003). *Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials*. American Society for Testing and Materials.
13. Ayadi, M., Segovia, C., Baffoun, A., Zouari, R., Fierro, V., Celzard, A., Msahli, S., Brosse, N. (2023). Influence of anatomy, microstructure, and composition of natural fibers on the performance of thermal insulation panels. *ACS Omega*, *8*(51), 48673–48688.
14. Beheshti, M. H., Firoozi, A., Jafarizaveh, M., Tabrizi, A. (2023). Acoustical and thermal characterization of insulating materials made from wool and sugarcane bagasse. *Journal of Natural Fibers*, *20*(2), 2237675.
15. Char, M., Khrissi, Y., Tilioua, A. (2025). Development of ecological thermal insulation materials based on renewable natural fiber waste and gum Arabic: Experimental study and characterization for use in semi-arid climates. *Results in Engineering*, 106510.
16. Choe, H., Sung, G., Kim, J. H. (2018). Chemical treatment of wood fibers to enhance the sound absorption coefficient of flexible polyurethane composite foams. *Composites Science and Technology*, *156*, 19–27.
17. Cintura, E., Nunes, L., Esteves, B., Faria, P. (2021). Agro-industrial wastes as building insulation materials: A review and challenges for Euro-Mediterranean countries. *Industrial Crops and Products*, *171*, 113833. https://doi.org/https://doi.org/10.1016/j.indcrop.2021.113833
18. Directorate General of Estates, Ministry of Agriculture, I. (2024). *Statistics of Estate Crops 2023–2025* 1. Directorate General of Estates, Ministry of Agriculture, Indonesia. www.ditjenbun.pertanian.go.id
19. Directorate General of Estates, M. of A. (2024). *Agricultural Statistics 2024*. Center for Agricultural Data and Information System Ministry of Agriculture Republic of Indonesia.
20. Dukarska, D., Walkiewicz, J., Derkowski, A., Mirski, R. (2022). Properties of rigid polyurethane foam filled with sawdust from primary wood processing. *Materials*, *15*(15), 5361.
21. Haghighatnia, T., Abbasian, A., Morshedian, J. (2017). Hemp fiber reinforced thermoplastic polyurethane composite: An investigation in mechanical properties. *Industrial Crops and Products*, *108*, 853–863.
22. Kausar, A. (2018). Polyurethane composite foams in high-performance applications: A review. *Polymer-Plastics Technology and Engineering*, *57*(4), 346–369.
23. Kusuma, H. S., Permatasari, D., Umar, W. K., Sharma, S. K. (2023). Sugarcane bagasse as an

environmentally friendly composite material to face the sustainable development era. *Biomass Conversion and Biorefinery*, 1–14.

24. Lazo, M., Puga, I., Macías, M. A., Barragán, A., Manzano, P., Rivas, A., Rigail-Cedeño, A. (2023). Mechanical and thermal properties of polyisocyanurate rigid foams reinforced with agricultural waste. *Case Studies in Chemical and Environmental Engineering*, *8*, 100392.
25. Limam, A., Zerizer, A., Quenard, D., Sallee, H., Chenak, A. (2016). Experimental thermal characterization of bio-based materials (Aleppo Pine wood, cork and their composites) for building insulation. *Energy and Buildings*, *116*, 89–95.
26. Long, Z., Wei, W., Chen, X., Wu, C., Liang, J., Lu, J., Wei, X., Wang, L. (2025). Superhydrophobic cellulose nanofiber aerogel composites with thermal insulation and solar absorption recycled from waste sugarcane bagasse pith. *Materials Today Communications*, *45*, 112217.
27. Mawardi, I., Aprilia, S., Faisal, M., Rizal, S. (2021). An investigation of thermal conductivity and sound absorption from binderless panels made of oil palm wood as bio-insulation materials. *Results in Engineering*, 100319. https://doi.org/https://doi.org/10.1016/j.rineng.2021.100319
28. Mawardi, I., Nurdin, N., Fakhriza, F., Rizal, S., Aprilia, S., Faisal, M., Jaya, R. P. (2023). Optimization of particle size and ramie fiber ratio on hybrid bio panel production from oil palm trunk as thermal insulation materials. *Journal of Ecological Engineering*, *24*(2), 39–49.
29. Otto, G. P., Moisés, M. P., Carvalho, G., Rinaldi, A. W., Garcia, J. C., Radovanovic, E., Fávaro, S. L. (2017). Mechanical properties of a polyurethane hybrid composite with natural lignocellulosic fibers. *Composites Part B: Engineering*, *110*, 459–465.
30. Oushabi, A., Sair, S., Abboud, Y., Tanane, O., El Bouari, A. (2017). An experimental investigation on morphological, mechanical and thermal properties of date palm particles reinforced polyurethane composites as new ecological insulating materials in building. *Case Studies in Construction Materials*, *7*, 128–137. https://doi.org/10.1016/j.cscm.2017.06.002
31. Pásztory, Z. (2021). An overview of factors influencing thermal conductivity of building insulation materials. *Journal of Building Engineering*, *44*, 102604. https://doi.org/https://doi.org/10.1016/j.jobe.2021.102604
32. Pérez, N. P., Travieso, J. A. R., Shelton, E. D. E., Pedroso, D. T., Machin, E. B., Tuna, C. E., Silveira, J. L. (2025). Unlocking the potential of sugarcane bagasse: a comprehensive analysis for advanced energy conversion. *Bioresources and Bioprocessing*, *12*(1), 60.
33. Ramlee, N. A., Jawaid, M., Yamani, S. A. K., Zainudin, E. S., Alamery, S. (2021). Effect of surface treatment on mechanical, physical and morphological properties of oil palm/bagasse fiber reinforced phenolic hybrid composites for wall thermal insulation application. *Construction and Building Materials*, *276*, 122239.
34. Raza, M., Abdallah, H. Al, Abdullah, A., Abu-Jdayil, B. (2022). Date palm surface fibers for green thermal insulation. *Buildings*, *12*(6), 866.
35. Sair, S., Oushabi, A., Kammouni, A., Tanane, O., Abboud, Y., El Bouari, A. (2018). Mechanical and thermal conductivity properties of hemp fiber reinforced polyurethane composites. *Case Studies in Construction Materials*, *8*, 203–212.
36. Samanta, K. K., Mustafa, I., Debnath, S., Das, E., Basu, G., Ghosh, S. K. (2022). Study of thermal insulation performance of layered jute nonwoven: a sustainable material. *Journal of Natural Fibers*, *19*(11), 4249–4262.
37. Schiavoni, S., Bianchi, F., Asdrubali, F. (2016). Insulation materials for the building sector: A review and comparative analysis. *Renewable and Sustainable Energy Reviews*, *62*, 988–1011. https://doi.org/https://doi.org/10.1016/j.rser.2016.05.045
38. Shao, H., Zhang, Q., Liu, H., Guo, W., Jiang, Y., Chen, L., He, L., Qi, J., Xiao, H., Chen, Y. (2020). Renewable natural resources reinforced polyurethane foam for use of lightweight thermal insulation. *Materials Research Express*, *7*(5), 55302.
39. Simamora, P., Simanjuntak, J., Sinulingga, K., Laksono, A. D. (2023). Mechanical properties of polypropylene composites with different reinforced natural fibers–a comparative study. *Journal of Ecological Engineering*, *24*(7).
40. Singh, M. K., Tewari, R., Zafar, S., Rangappa, S. M., Siengchin, S. (2023). A comprehensive review of various factors for application feasibility of natural fiber-reinforced polymer composites. *Results in Materials*, *17*, 100355.
41. Sulaiman. (2025). Rice Husk, Rice Husk Ash, and Their Applications. In *Rice Husk Biomass: Processing, Properties and Applications* 43–54. Springer.
42. Wang, J., Zhang, C., Deng, Y., Zhang, P. (2022). A Review of research on the effect of temperature on the properties of polyurethane foams. *Polymers*, *14*(21), 4586.
43. Zhao, R., Guo, H., Yi, X., Gao, W., Zhang, H., Bai, Y., Wang, T. (2020). Research on thermal insulation properties of plant fiber composite building material: a review. *International Journal of Thermophysics*, *41*, 1–18.