Multi-Criteria Optimization of Rice- and Coconut Husks Reinforced Polyurethane Composites as Substitute for Rubber Foam in Air Conditioning

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This study presents a novel approach to mitigating the environmental impact of non-degradable industrial insulators used in air conditioning pipe. It focused on evaluating and optimizing polymer composites reinforced with rice husks and coconut husks as sustainable thermal insulation materials. This study involved two main phases: First, evaluation of the thermal and mechanical properties of rice and coconut husks reinforced polyurethane composites. Second, determination of the optimal reinforcement ratio using a hybrid multi-criteria decision-making (MCDM) methodology that integrates the Analytical Hierarchy Process (AHP) and the Additive Ratio Assessment (ARAS) techniques. Composites were fabricated with reinforcement ratios ranging from 5% to 25% by weight. Thermal conductivity results, ranging from 0.041 to 0.0486 W/m·K, confirmed the insulative potential of all composite samples, which corresponded to the range reported for industrial thermal insulators. Mechanical testing revealed enhanced tensile strength, particularly with 25 wt% coconut husks, achieving a value of 0.744 MPa. The ARAS method concluded that the optimal composition for insulation performance is 10% rice husk and 25% coconut husk reinforcements. This study advances sustainable thermal insulation materials. In addition, it offers a systematic framework for selecting the optimal reinforcement ratio for biocomposites.

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INTRODUCTION

Recent years have seen a strong emphasis on improving energy efficiency. Studies have shown that air conditioning systems are responsible for nearly 50% of the total electricity consumption in office buildings and around 30% in residential buildings (Ersöz and Yildiz 2016a). Researchers have determined that insulating refrigerated pipes effectively reduces energy consumption and improves the efficiency of air conditioning

systems (Yildiz and Ali Ersöz 2015). Concerns have been raised about synthetic insulators because of their non-biodegradable and non-recyclable nature, which poses significant risks to ecosystems and may result in long-term environmental damage (Cássio *et al*. 2022). Accordingly, the development of eco-friendly, biodegradable, and low-cost thermal insulation materials is needed. At the same time, such materials would offer a sustainable alternative to traditional options with low thermal conductivity and low environmental impact (Liuzzi *et al*. 2023).

According to the ASHRAE Standard 90.1-2022, all refrigerant lines operating below ambient temperature are to be insulated. The standard specifies minimum insulation thicknesses based on pipe diameter and heat loss coefficients to ensure compliance with thermal performance and energy efficiency requirements. Typically, the minimum insulation thickness ranges from 12 to 125 mm, depending on the pipe size and operating temperature, while the insulation material should have a reference thermal conductivity between 0.033 and 0.049 W/m· K to provide effective thermal resistance and prevent condensation (Issenbeck *et al*. 2022). In another study, researchers emphasized that the selection of insulation materials plays a crucial role, highlighting that the recommended criteria include low thermal conductivity, moisture resistance, durability, cost, and environmental sustainability (Jensen *et al.* 2023; Lakatos *et al*. 2025). In context, a study indicated that polymeric composites reinforced with plant fibers provide various advantages, such as availability of raw materials, low cost, excellent physical, mechanical, thermal properties, and biodegradability (Faria *et al*. 2023). A study by Bandaranayake *et al*. (2023) found that coconut husk fibers can effectively reduce heat transfer, making them a suitable material for thermal insulation applications. As a result, coconut husk has been extensively utilized to reinforce polymer foams, such as polyurethane, in applications related to building materials and thermal insulation (Sharma and Prasath Kumar 2023). In addition, studies have reported that incorporating rice husk into polyurethane foam can improve its properties, including density, water absorption, and tensile strength (Muthuraj *et al*. 2019).

Studies conducted by Marín-Calvo *et al*. (2023) and Singh *et al*. (2024) highlighted the chemical characteristics of rice husks, reporting a cellulose content of 35 to 45%, hemicellulose 19 to 25%, and lignin around 20%. The high cellulose and silica content of rice husk contribute to low thermal conductivity and improved resistance to water absorption, thereby enhancing their potential as sustainable thermal insulation materials. In this context, a study reported that the wood fiber, bamboo fiber, rice husk were added into the polyurethane foam at 25%, 30%, 35% weight ratio, respectively, and it was found that the composites greatly enhanced the mechanical strength (Shao *et al.* 2020). According to most academic studies, the mechanical performance of natural fiber composites is influenced by several factors, including the fiber type, fiber length, orientation, weight fraction, fiber bonding, the selected polymer matrix, and the presence of voids (Asfaw *et al*. 2024). On the other hand, the mechanical performance of polymer composites tends to improve with increasing fiber reinforcement ratios. Sayeed *et al*. (2023) investigated polypropylene composites reinforced with three types of natural fibers jute, kenaf, and pineapple leaf fiber at fiber loadings of 30%, 35%, and 40% by weight. Their results revealed that the tensile, flexural, and impact strengths of the composites increased markedly with higher fiber contents compared to the neat polypropylene matrix. The tensile strength ranged from 43 to 58 MPa, flexural strength from 53 to 67 MPa, and impact strength from 25 to 46 kJ/m², whereas the unreinforced PP exhibited lower values of 36 MPa, 53 MPa, and 22 kJ/m². Moreover, a challenge arises in selecting the optimal

reinforcement ratios of natural fibers for manufacturing thermal insulation, as most of the thermal and mechanical properties of natural fiber composite reinforcement ratios fall within the limits of conventional insulation (Alazzawi *et al.* 2024). As a result, it is difficult to make a decision regarding the most suitable reinforcement ratio for use as insulation.

Previous literature has emphasized the significance of using multi-criteria decision-making techniques (MCDM) to identify the best alternative by comparing it with other options (Fatmayati *et al.* 2023). The Analytical Hierarchy Process (AHP) is useful to determine the weight of each criterion that can evaluate the importance of the criterion and the influence which the criterion make in the selection of the alternatives (Mansor *et al.* 2013). Some researchers have also integrated Additive Ratio Assessment (ARAS) approach with AHP to improve the evaluation process and support decision-making in selecting the best alternatives (Khan *et al.* 2024). To date, no study has evaluated natural fiber-reinforced composites as sustainable thermal insulators for air conditioning pipes. Moreover, the literature lacks integrated MCDM-based analyses to determine their optimal reinforcement ratio. Accordingly, this study addresses the following two key objectives: The first goal was to study flexural polyurethane foam reinforced with two kinds of natural fibers, rice husks and coconut husk, as thermal insulation of air conditioning piping systems. Second, the MCDM process was applied to determine the optimal reinforcement ratio for the prepared composites. This study ultimately sought to establish a methodology for evaluating biocomposites as thermal insulators and to determine the optimal natural fiber reinforcement ratios.

EXPERIMENTAL

Materials

The flexible polyurethane was prepared using polyether polyol (propylene oxide ethylene oxide) with a density of 1.050 ± 05 g/cm^3 and dynamic viscosity of 800 to 1000 mPa.s, and methylene diisocyanate with a viscosity of 150 mPa.s and specific gravity of 1.19, acquired from Shandong INOV New Material Co., Ltd. (China). The rice husks and coconut husks were supplied by That Plant Doctor (Malaysian farms).

Methods

Husks were first rinsed with distilled water to remove dust and other impurities, then oven dried at 60 °C for 24 h to ensure complete removal of moisture. Rice husks used in this study had an average length of approximately 10 mm and a width ranging from 1 to 2 mm. In contrast, coconut husks were cut into lengths between 1 and 6 cm, consistent with values reported in references (Krishnamoorth and David 2015; Salaenoi *et al*. 2024). They were then mixed with the polyol using a mechanical stirrer (IKA RW20 Digital, IKA-Werke GmbH & Co. KG, Staufen, Germany) at a rotational speed of 2000 rpm for 30 s to achieve a homogeneous mixture. Subsequently, methylene diisocyanate was added to the mixture at a ratio of 100:60, followed by further mixing at 2000 rpm for approximately 30 s. The resulting foam mixture was then poured into cylindrical molds measuring 12 cm in height and 7 cm in diameter (see Fig. 1). Six compounds with different weight percentages were prepared from polyurethane foam reinforced with rice husks and coconut husks ranging from 0 to 25%. Table 1 presents the husk contents used in each composite. The surface of the composite samples was inspected using an Olympus DSX1000 optical

microscope (Olympus Corporation, Tokyo, Japan) to evaluate the distribution of husks and the cell morphology, as illustrated in Fig. 2.

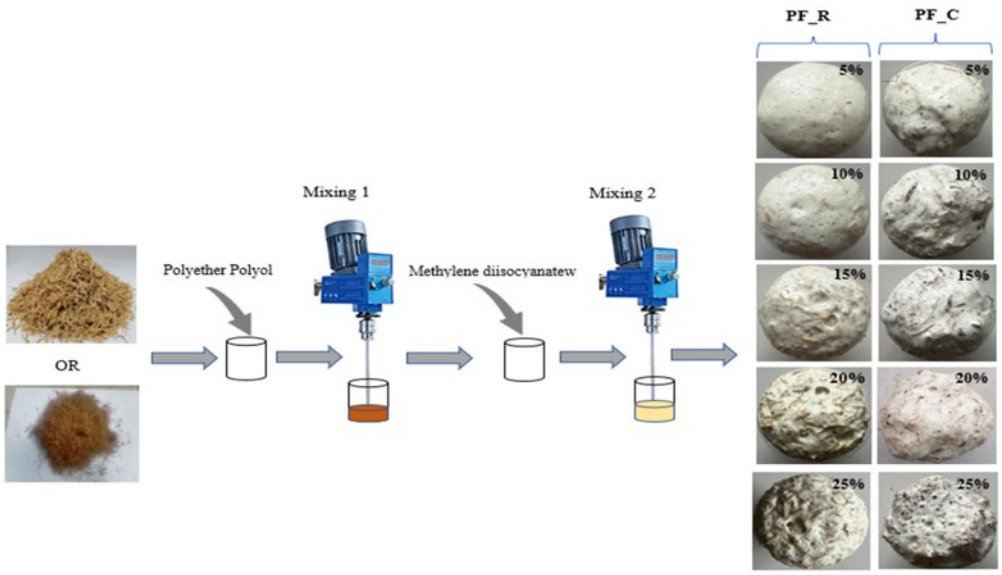

Fig. 1. Schematic representation of the fabrication process for rice husk-reinforced polyurethane composite material

Fig. 2. Olympus DSX1000 optical microscope

Table 1. Polyurethane Foam Formulations Reinforced Rice Husk with Coconut Husks

Sample	Matrix mixing ratio rice husk and coconut husks
0%wt	Pure polyurethane foam (PF)
5%wt	95% PU in combination with 5% Rice Husk (PF_R) or 5% Coconut Husk (PF_C) in composites
10%wt	90% PU in combination with 10% Rice Husk (PF_R) or 10% Coconut Husk (PF_C) in composites
15%wt	85% PU in combination with 15% Rice Husk (PF_R) or 15% Coconut Husk (PF_C) in composites
20%wt	80% PU in combination with 20% Rice Husk (PF_R) or 20% Coconut Husk (PF_C) in composites
25%wt	75% PU in combination with 25% Rice Husk (PF_R) or 25% Coconut Husk (PF_C) in composites

Measurements and Characterizations

Mechanical testing

The ultimate tensile strength and elongation at break for the prepared composites were measured using an Instron 3366 universal testing machine at a crosshead speed of 500 mm/min and a load capacity of 5 kN, in accordance with the ASTM D3574-17 standard testing method (Husainie *et al*. 2020). Dumbbell-type specimens (ASTM D412A) were used for the tests, as illustrated in Fig. 3, which shows the tensile testing setup. Six different reinforcement ratios of husks (0, 5, 10, 15, 20, and 25 wt%) were examined. Each test was performed on five replicated specimens for each reinforcement ratio of husks to ensure data reliability. The obtained results were statistically analyzed, and the mean and standard deviation were calculated. The standard deviation values are represented as error bars in the respective figures.

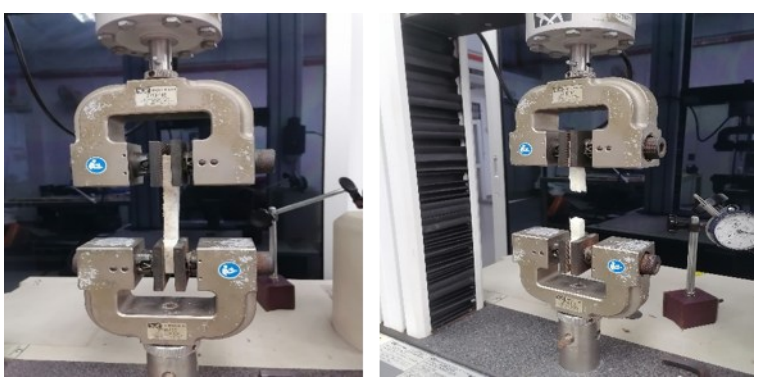

Fig. 3. Experimental setup for tensile strength test

Water absorption

Water absorption characteristics of the composite samples were studied as per the ASTM C272 standard test method, as similarly applied by Jang *et al*. (2021) for comparable polyurethane composite. The specimens were prepared with the dimensions of 50 mm × 50 mm × 25 mm and weighed using an electronic weighing machine (Mettler Toledo, Model: JP6002G, Mettler-Toledo International Inc., Switzerland), with a maximum

capacity of 6200 g and a readability of 0.01 before being immersed in distilled water for 24 h at room temperature. Then, samples were taken out and wiped with absorbent paper to remove the surface moisture, and reweighed. The water absorption percentage was calculated using Eq. 1.

$$\text{Water absorption (\%)}, W = \frac{W_1 - W_2}{W_1} \times 100 \quad (1)$$

where (W_2, W_1) represent the weight values before and after immersion, respectively.

Thermal conductivity measurement

The thermal conductivities for polyurethane foam reinforced with rice and coconut husks were measured using a KD2 Pro thermal properties analyser manufactured by Decagon Devices Inc. Pullman, WA (Decagon Devices 2016). The instrument operates within a measurement range of 0.02 to 2.00 W/m· K and provides a thermal conductivity value within 2 to 10 minutes. Other researchers have used it with various insulating materials (Rojas *et al*. 2023). The KD2 Pro analyzer used the phenomenon of the heat source of the transient line to analyze the thermal properties of materials following Standard IEEE 442-1981 and ASTM D5334-08 (Decagon Devices 2016). In this study, readings were taken at 10-minute intervals under laboratory conditions at an average temperature of 25 °C$\pm$1.

Multi-Criteria Decision-Making Methodology

Multi-Criteria Decision Making (MCDM) is a systematic method used to assess and rank alternatives based on several criteria (Taherdoost and Madanchian 2023). Various MCDM methods have been developed by different authors. The primary differences between these methods lie in the weighting techniques used for criteria and the approach to representing and evaluating preference criteria (Bączkiewicz *et al*. 2021). A study by Jusufbašić (2023) demonstrated that MCDM encompasses a variety of methods designed to assess and prioritize multiple conflicting criteria in decision-making. Among the most widely recognized techniques are the Analytic Hierarchy Process (AHP) and the Additive Ratio Assessment (ARAS) methods, both of which are extensively used in numerous fields to facilitate effective decision-making (Khan *et al*. 2024).

The Analytical Hierarchy Process

Analytical Hierarchy Process is a prevalent multi-criteria decision-making methodology established by Saaty (1980). This approach is effective in addressing complex decision problems involving multiple criteria and alternatives (Majji *et al.* 2023). It has been successfully applied in various fields, including renewable energy systems, agriculture, and industrial applications (Howari *et al.* 2023; Roy *et al.* 2024). The AHP process begins by defining the decision goal, selecting the relevant criteria, and identifying the possible alternatives, all of which are structured hierarchically (Deretarla *et al.* 2023). A pairwise comparison matrix is then constructed, based on expert input and previous studies (Aksakal *et al.* 2022). This step helps to determine the relative importance of each criterion. The following outlines the steps required to complete the AHP decision-making process.

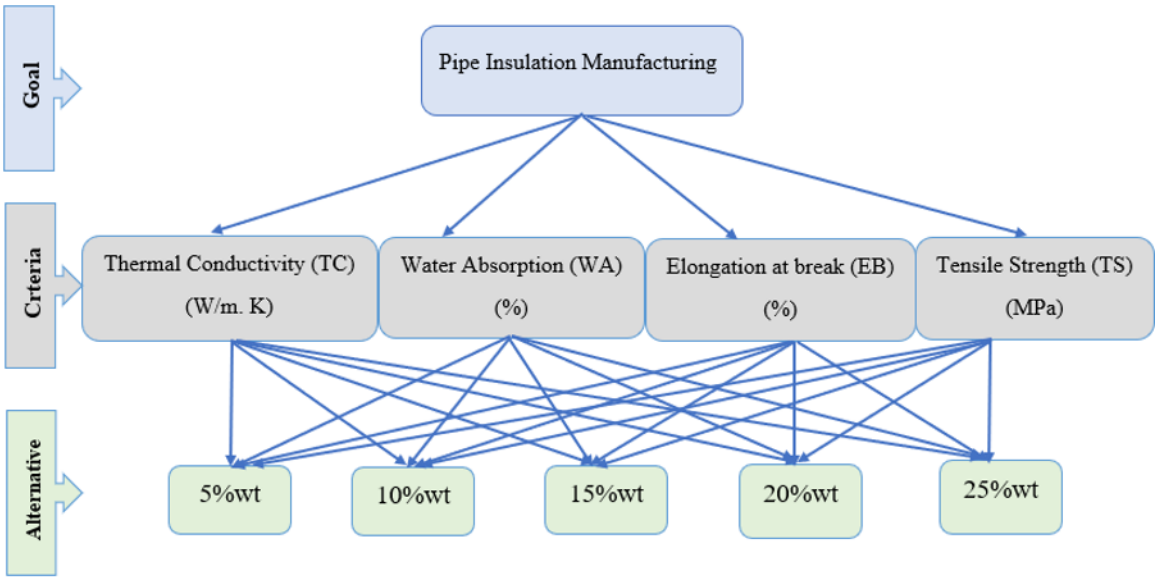

Fig. 4. Analytical hierarchy process of goals, criteria, and alternatives

Step 1: A pyramid structure was designed, as shown in Fig. 4, where the top of the pyramid represents the objective of the study, which is the design of air conditioning pipe insulation, the second level of the pyramid outlines the key criteria that must be considered when selecting the optimal insulation material, and the third level identifies alternative materials.

Step 2: A 4 × 4 pairwise comparison matrix was created to assess the relative importance of each criterion, using scale of pair-wise comparison (Saaty 1987) as detailed in Table 2. The pairwise comparison results are summarized as follows:

- The thermal conductivity coefficient (TC) was assigned a value of one when compared with itself, indicating equal importance.
- The thermal conductivity (TC) is three times more important than water absorption (WA).
- The thermal conductivity coefficient (TC) is four times more important than elongation at break (EB).
- The thermal conductivity coefficient (TC) is five times more important than tensile strength (TS).

Similarly, the water absorption criterion was considered more important than elongation at break and tensile strength, with importance of two and three, respectively, and was assigned a value of 1 when compared with itself, following the same AHP methodology.

Table 2. Pair-wise Comparison Matrix

Criteria	TC	WA	EB	TS
TC	1	3	4	5
WA	0.3333	1	2	3
EB	0.25	0.5	1	3
TS	0.2	0.3333	0.3333	1

Note: TC = Thermal Conductivity (W/m. K), WA = Water Absorption (%), EB = Elongation at break (%), and TS = Tensile Strength (MPa)

Step 3: A pairwise comparison matrix was normalized for each criterion using Eq. 2. Then, the relative importance of each criterion was calculated by averaging the normalized values in each row, as shown in Eq. 3:

$$N_{ij} = \frac{\mathrm{X_{ij}}}{\text{Sum of every column}} \tag{2}$$

$$\text{Criteria weights} = \frac{\sum N_{ij}}{n} \tag{3}$$

Step 4: The weighted sum was calculated by multiplying the criteria weights with the pairwise comparison matrix. Then, the total for each row was determined.

Step 5: The principal Eigenvalue (λ_{max}) was calculated using Eq. 4.

$$\lambda_{max} = \sum_{i=1}^{n} \frac{E_i}{n} \tag{4}$$

where $E_i = \frac{\text{Weighted sum}}{\text{Criteriaweight}}$; and n = The number of criteria

Step 6: The consistency index (*CI*) was calculated using Eq. 5 and the consistency ratio (CR) using Eq. 6, to assess whether the weights of the obtained standards are acceptable or not. The consistency ratio is considered acceptable if CR < 0.1.

$$CI = \frac{\lambda_{\max - n}}{n} \tag{5}$$

$$CR = \frac{CI}{RI} \tag{6}$$

where *RI* refers to (Random index) is given Table 3

Table 3. Random Index Values for Various Values (Saaty 1987)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.6	0.9	1.1	1.2	1.3	1.4	1.4	1.5

The Additive Ratio Assessment

The Additive Ratio Assessment (ARAS) technique is a MCDM method first introduced by Zavadskas *et al.* (2010). This approach emphasizes the relative ranking of criteria defined by the user (Liu *et al.* 2020). The ARAS methodology is based on the additive ratio concept, enabling the aggregation of various criteria into a single score for each alternative. This means that alternatives with higher rankings receive higher scores, while those with lower rankings are assigned lower scores (Zavadskas *et al.* 2010). Then

the highest-ranking alternative is determined as a model for manufacturing the insulation. ARAS method includes the steps shown below.

Step 1: A decision matrix is created for the criteria and alternatives as seen in Eq. 7, with four criteria and five alternatives selected. Additionally, the optimal value of each criterion in the columns is determined, where the maximum and minimum values are selected based on the importance of the criterion for the application as an insulator. Specifically, the optimum value for thermal conductivity and water absorption is the lowest value, while the highest value is considered optimal for tensile stress and elongation at break.

$$\boldsymbol{X}_{\mathbf{ij}} = \begin{bmatrix} X_{0i} & \cdots & X_{0j} & \cdots & X_{0n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ X_{i1} & \cdots & X_{ij} & \cdots & X_{ni} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ X_{ni} & \cdots & X_{mj} & \cdots & X_{mn} \end{bmatrix} \tag{7}$$

In Eq. 7, $i = 0, m$; and j = 1, n. Also, m = number of alternatives and n = number of criteria. X_{ij} refers to the performance value of alternative i against criterion j. X_{0j} = the optimum value of criterion.

Step 2: Normalized decision matrix

This stage will normalize both the beneficial and non-beneficial features of all criteria and arrange them into a matrix. The formulas provided below will be used to identify the beneficial factors using Eq. 8 and the non-beneficial factors using Eq. 9.

$$\bar{X}_{ij} = \frac{X_{ij}}{\sum_{i=0}^{m} X_{ij}} \tag{8}$$

$$X_{ij} = \frac{1}{X_{ij}} \; ; \; \overline{X}_{ij} = \frac{X_{ij}}{\sum_{i=0}^{m} X_{ij}} \tag{9}$$

Step 3: Finding the weight of the normalized matrix

The weight of the normalized decision matrix is found by multiplying the standard weights extracted using AHP technique by each factor of the decision matrix using Eq. 10.

$$D_{ij} = \text{Normalized decision matrix} \times \text{Criteria weights} \tag{10}$$

where D_{ij} = weight of the normalized matrix

Step 4: Determine the value of the optimality function for each alternative

After getting the normalized matrix weights, the following step was conducted to determine the optimal value using Eq. 11.

$$S_i = \sum_{j=1}^{n} D_{ij} \tag{11}$$

where S_i = Optimum value for alternative i

Step 5: Calculation of utility degree (K_i) and Ranking levels

In the final stage, the utility score for each characteristic was calculated using Eq. 12 to find the ranking levels The utility value helps identify the best alternative based on the score each alternative receives. The alternative with the highest score is considered the best candidate for application.

$$K_i = \frac{S_i}{S_o} \tag{12}$$

where K_i = an alternative ranking value, S_o = optimum value for the optimal alternative, and Si = optimum value for alternative i.

RESULTS AND DISCUSSION

Thermal Conductivity of Polyurethane Composites

Figure 5 illustrates the increase in thermal conductivity of polyurethane foam reinforced with rice husks and coconut husks. For the rice husk reinforced composites, the thermal conductivity ranged from 0.043 to 0.048 W/m·K, indicating an increase of up to 25.9% compared to pure polyurethane foam. In contrast, the thermal conductivity results of coconut husk composites showed a range from 0.041 to 0.046 W/m·K reflecting a 19.1% increase. This difference in values is likely due to the shape and arrangement of the husks within the polyurethane matrix. where it is plausible that the irregular distribution of husks enhances the number of contact points within the foam, thereby promoting an increment in thermal transfer. This finding aligns with that of Zhang *et al*. (2013) who reported that randomly distributed fibers exhibit higher thermal conductivity compared to those uniformly distributed fibers. Furthermore, the observed increment in thermal conductivity may be attributed to the reduction of voids within the polyurethane foam as the reinforcement ratio increases.

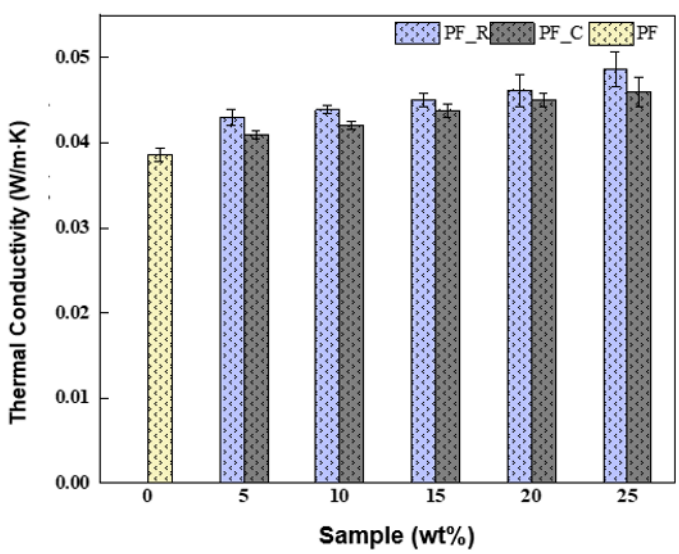

Fig. 5. Thermal conductivity values variations of polyurethane foams reinforced with different weight percentages of rice husks and coconut husks. Note: PF_R = Polyurethane foam reinforced with Rice husks, PF_C= Polyurethane foam reinforced with Coconut husks, and PF= pure (unreinforced) Polyurethane foam.

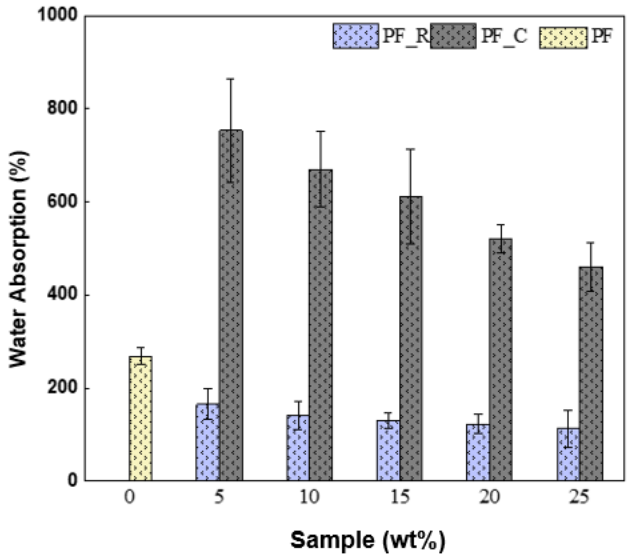

Fig. 6. Water absorption values for rice husks and coconut husks reinforced polyurethane foam composites

Table 4. Comparison of Thermal Properties between Fabricated Composites and Commercial Insulators

Insulation material	Thermal conductivity (W/m. K)	Reference
Expanded polystyrene	0.035 – 0.04	(Moran et al., 2018)
Extruded polystyrene	0.030 – 0.040	(Moran et al., 2018)
Flexible elastomeric foam	0.035 – 0.045	(Porzuczek, 2024)
Neoprene foams	0.050 – 0.060	(Moran et al., 2018)
Cork	0.037 – 0.050	(Hung Anh & Pásztory, 2021)
Glass wool	0.03 – 0.045	(Hung Anh & Pásztory, 2021)
Rock wool	0.033 – 0.045	(Hung Anh & Pásztory, 2021)
Polyethylene foam	0.037 – 0.049	(Porzuczek, 2024)
Polyurethane composites reinforced coconut husk	0.041 – 0.046	Present study
Polyurethane composites reinforced rice husk	0.043 – 0.048	Present study

These voids, predominantly filled with air having a thermal conductivity coefficient of 0.026 W/m·K, are gradually diminished with rising reinforcement content, which increases thermal conductivity (Sair *et al.* 2018). Notably, the thermal conductivity coefficient of rice husk reinforced composites was higher than that of coconut husk reinforced composites, due to the inherent thermal conductivity of the husks themselves. The minimum thermal conductivity coefficient of rice husks combined with resin was reported to be 0.08 W/m·K, while coconut husk fiber mixed with resin exhibits the lowest thermal conductivity value of 0.0410 W/m·K (Shah *et al.* 2024). Despite the increase in the thermal conductivity coefficient, the prepared composites continued to be effective as thermal insulators, as materials with thermal conductivity values less than or equal to 0.050 W/m· K are classified as thermal insulators (Lobo-Ramos *et al.* 2023). On the other hand, the results presented in Table 4 provide a detailed comparison of the thermal conductivity

coefficients between the fabricated composites and commercial insulation materials common in air conditioning systems (Ersöz and Yildiz 2016b; Porzuczek 2024). The findings clearly demonstrate that the polyurethane composites reinforced with rice husk and coconut husk exhibited strong potential for application as sustainable thermal insulation materials in air conditioning systems.

Water Absorption Behavior of Polyurethane Composites Reinforced with Rice Husk and Coconut Husk

The water absorption behavior of polyurethane composites reinforced with rice husk and coconut husk was investigated, and results are shown in Fig. 6. The polyurethane foam 0 wt% exhibited a water absorption value of 269%, which indicates its high tendency for moisture uptake due to the presence of interconnected open cells that facilitate water diffusion through the foam see Fig. 7. For rice husk reinforced composites, water absorption decreased progressively from 165.5% at 5 wt% to 112.1% at 25 wt%, representing a reduction of more than 58% compared to the pure foam. This reduction can be attributed to the lower water absorption capacity of rice husks, which have a silicon cellulose membrane that limits moisture uptake (Husainie *et al.* 2021). In contrast, composites incorporating coconut husks exhibited an increase in water absorption, reaching 753% at 5% husk content, followed by a decline to 460.2% at 25% husk loading, representative of a 63.6% reduction. In this context, the water absorption by the polyurethane composite reinforced with 25 wt% coconut husks was approximately 71% higher than that of the pure foam. Prior investigations have demonstrated that coconut fibers consist of lignocellulosic materials containing hydroxyl groups, which attract water molecules. Consequentially, these fibers swell and generate voids, further increase the composites water absorption (Mittal and Chaudhary 2018). In addition, this increase can be attributed to the cell damage for polyurethane foam resulting from increase coconut husks loading ratios, which makes foam more susceptible to water absorption, as illustrated in Fig. 8. This observation is in agreement with the findings reported by Zakrzewska *et al.* (2024). Despite these variations, both composites showed similar tendencies, with water absorption initially rising with fiber content but subsequently decreasing as the fiber load increases. The coconut husk composite absorbed far more water than the rice husk composite, implying that coconut fibers have a stronger inclination to draw and retain water. These findings correspond with prior research (Ahmad *et al.* 2022; Głowacz-Czerwonka *et al.* 2023), which reveal comparable tendencies in water absorption behavior.

Mechanical Properties of Polyurethane Composites

Figures 7, 8, and 9 show the results of mechanical tests of rice and coconut husks-based composites. The addition of rice husks led to a notable enhancement in tensile strength, which increased by 26.9% at a reinforcement ratio of 25 wt%, compared to the pure foam.

This improvement is attributed to the effective interfacial bonding between the natural fibers and the polymer matrix, which minimizes slippage during stress, in agreement with the findings of previous studies (Kumar *et al.* 2023; Li *et al.* 2023). (Mohammed 2022) reported that interfacial bonding in natural fiber reinforced polymers arise from four key mechanisms: mechanical interlocking, hydrogen bonding, van der Waals, and electrostatic or chemical interactions. These forces enhance stress transfer, reduce fiber pull-out under load, and improve the tensile strength and stiffness of the composites.

Furthermore, the addition of rice husks lowered elongation at break from 24.3% to 14.1%. Young's modulus also saw a significant improvement of 156% at 25 wt% rice husk content. This enhancement was attributed to the natural hardness of the rice husks resulting in improved resistance against deformation, as reported in literature (Olcay and Kocak 2021). Similarly, the addition of coconut husks to polyurethane foam significantly improved tensile strength to 0.744 MPa at 25 wt%. This improvement was driven by factors such as the nature, shape, and size of the husk particles, which provide a high surface area for stress absorption, as well as strong bonding between the coconut husks and the polyurethane matrix. Moreover, the increment in coconut husks content led to a progressive rise in Young's modulus, which peaked at 0.048 MPa at a reinforcement ratio of 25 wt%. This enhancement is attributed to the intrinsic rigidity of coconut husks, which restricts the deformability of the composite material, as supported by prior investigations (Uchechukwu Chris-Okafor 2017).

In addition, Fig. 9 indicates a difference in the Young's modulus between the coconut husk composites and those reinforced with rice husk. This variation can be attributable to the type of the fillers and their dispersion throughout the polyurethane foam. In context, elongation at break for the coconut husk composite decreased from 22.5% to 13.2% with increasing filler content. This reduction may be attributed to fiber agglomeration at higher coconut husk loadings, creating unbonded regions that promote crack initiation. These findings are also consistent with other studies (Jumaidin *et al.* 2024).

On the other hand, all principal parameters were integrated, as presented in Figs. 10 and 11, to offer a comprehensive insight into the correlation between the thermal and mechanical performance of polyurethane composites reinforced with rice and coconut husks. The coconut husk composites exhibited higher initial water absorption compared to the rice husk composites, which can be mainly attributed to the hydrophilic nature and hollow structure of the coconut husks. In contrast, the rice husk composites maintained lower water absorption across all reinforcement levels, owing to their silica-rich surface, which serves as against water absorption.

In terms of mechanical behavior, both composites exhibited notable enhancements in tensile strength and Young's modulus with increasing husk content. This improvement can be attributed to good interaction between the husks and polyurethane matrix, which facilitated efficient stress transfer and uniform load distribution throughout composites. The maximum Young's modulus reached 0.048 MPa for the coconut husk composites and 0.019 MPa for the rice husk composites, indicating that coconut husks impart greater stiffness. Furthermore, the thermal conductivity exhibited a slight increase in both composites but continued to fall within the range of commercial insulation materials employed for air-conditioning systems.

Overall, the rice husk composites exhibited better thermal insulation efficiency and lower water uptake, while the coconut husk composites demonstrated higher rigidity and mechanical strength. Therefore, both composites exhibited promising potential to serve as sustainable alternatives to rubber foam for thermal insulation in air-conditioning systems.

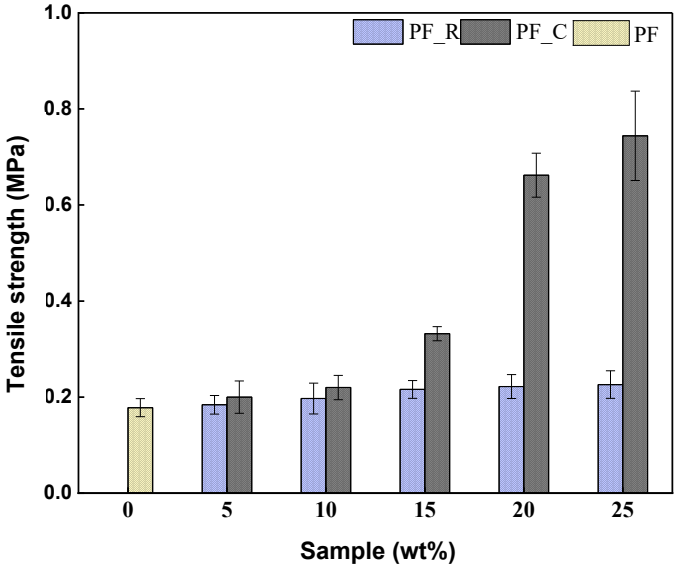

Fig. 7. Tensile strength values of polyurethane foam composites reinforced rice husks and coconut husks

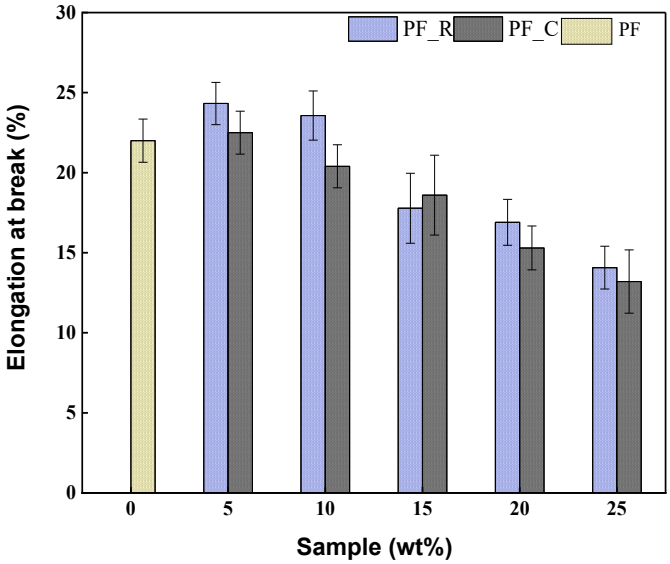

Fig. 8. Elongation values of polyurethane foam composites reinforced rice husks and coconut husks

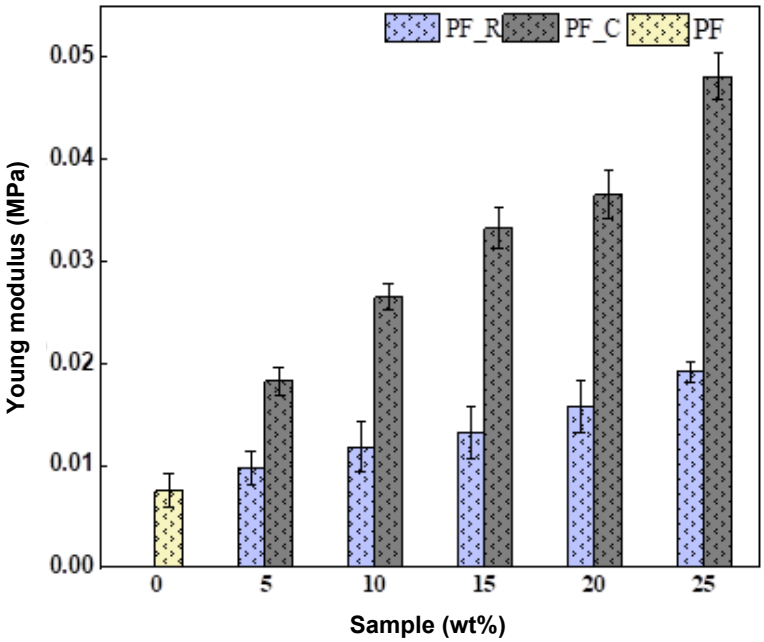

Fig. 9. Young's modulus according to polyurethane foam composites reinforced rice husk and coconut husk

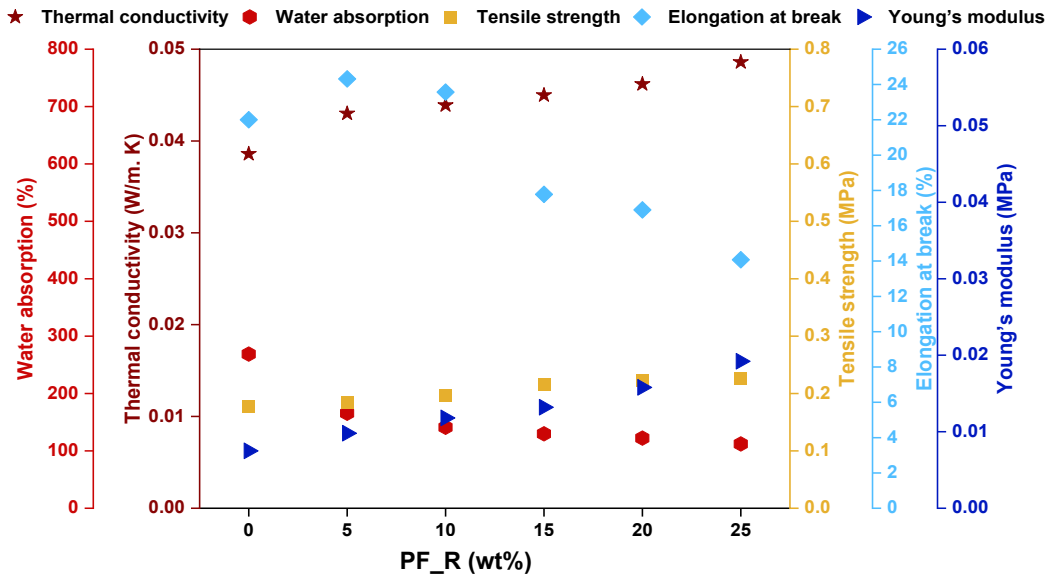

Fig. 10. Correlation between thermal conductivity and mechanical properties of rice husk reinforced polyurethane composites

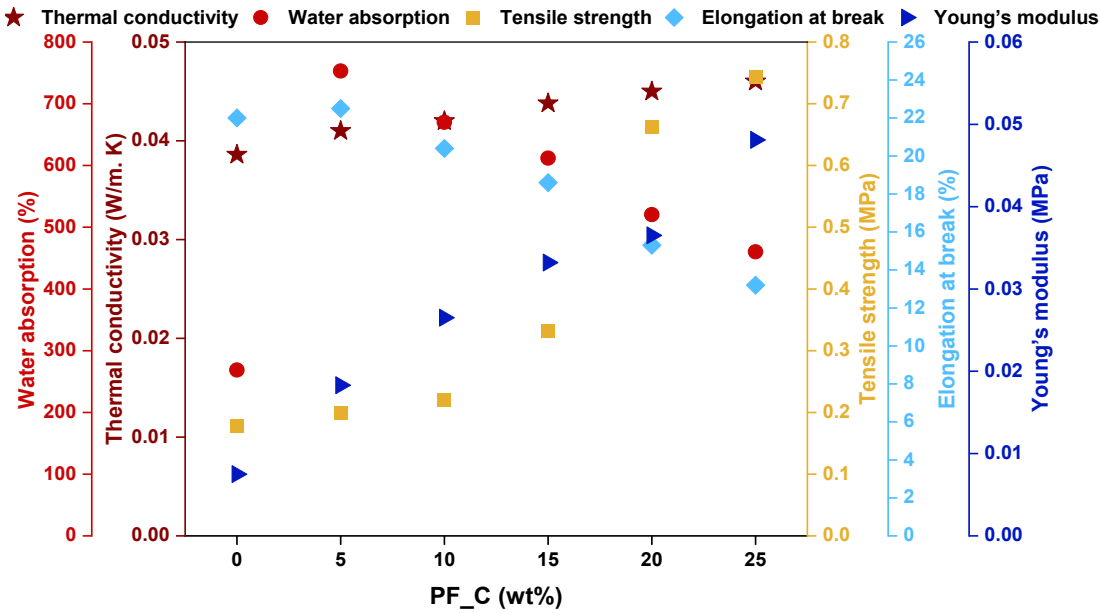

Fig. 11. Correlation between thermal conductivity and mechanical properties of coconut husk reinforced polyurethane composites

Digital Microscopy Analysis

Based on the digital microscopy analysis of the cross-sections of the specimens Figs. 12 and 13, the incorporation of rice husks and coconut husks into the polyurethane foam significantly affected the cellular morphology and internal structure of the composites, resulting in irregular cell formation and a noticeable reduction in cell wall thickness. Similar observations have been widely reported in the literature, where several researchers have confirmed that the incorporation of lignocellulosic fillers tends to weaken the cellular structure of polyurethane foams, thereby influencing their mechanical and thermal performance (Dukarska *et al.* 2022).

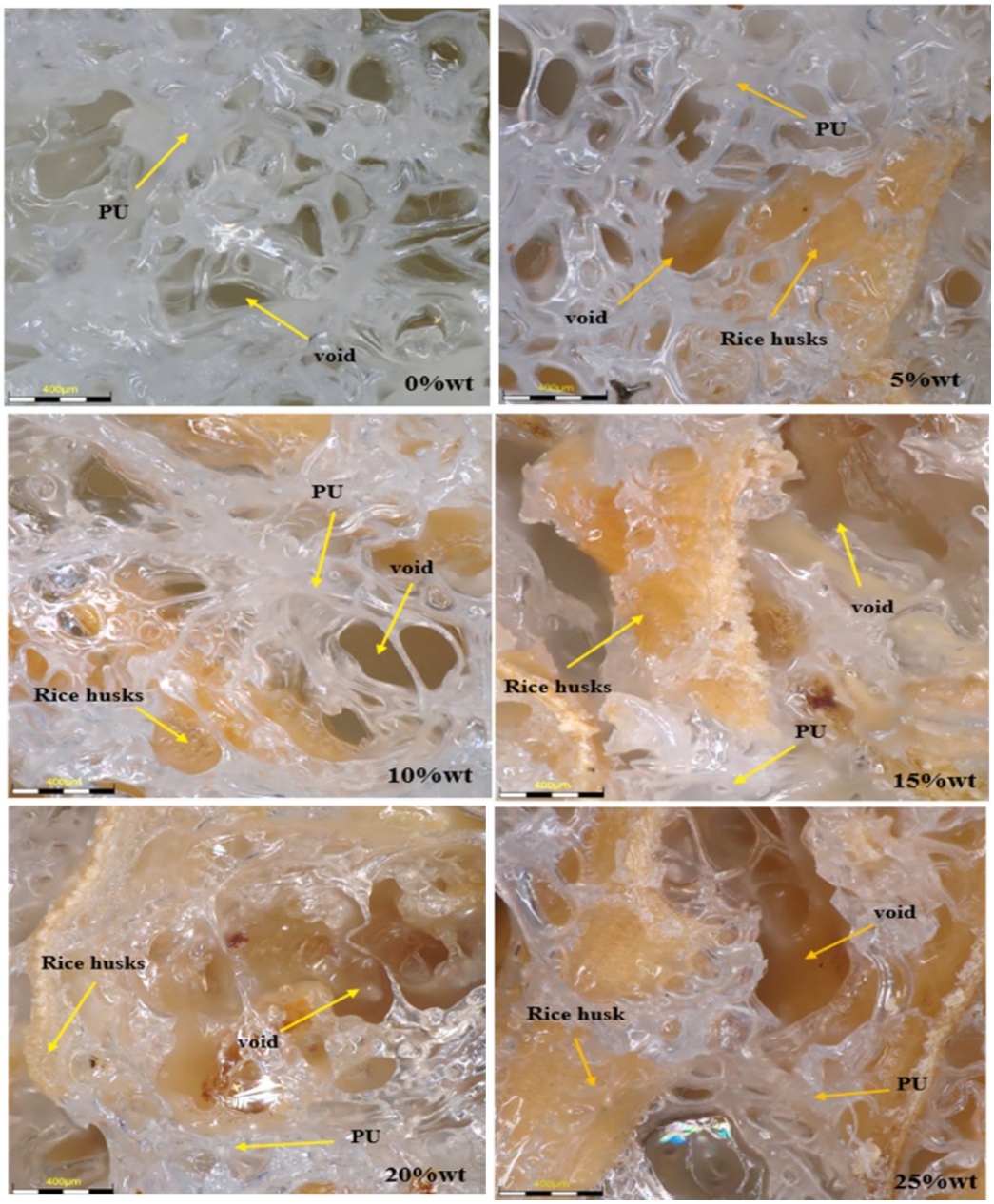

Fig. 12. Digital microscope images of polyurethane composites reinforced with rice husk at concentrations ranging from 5% to 25% by weight

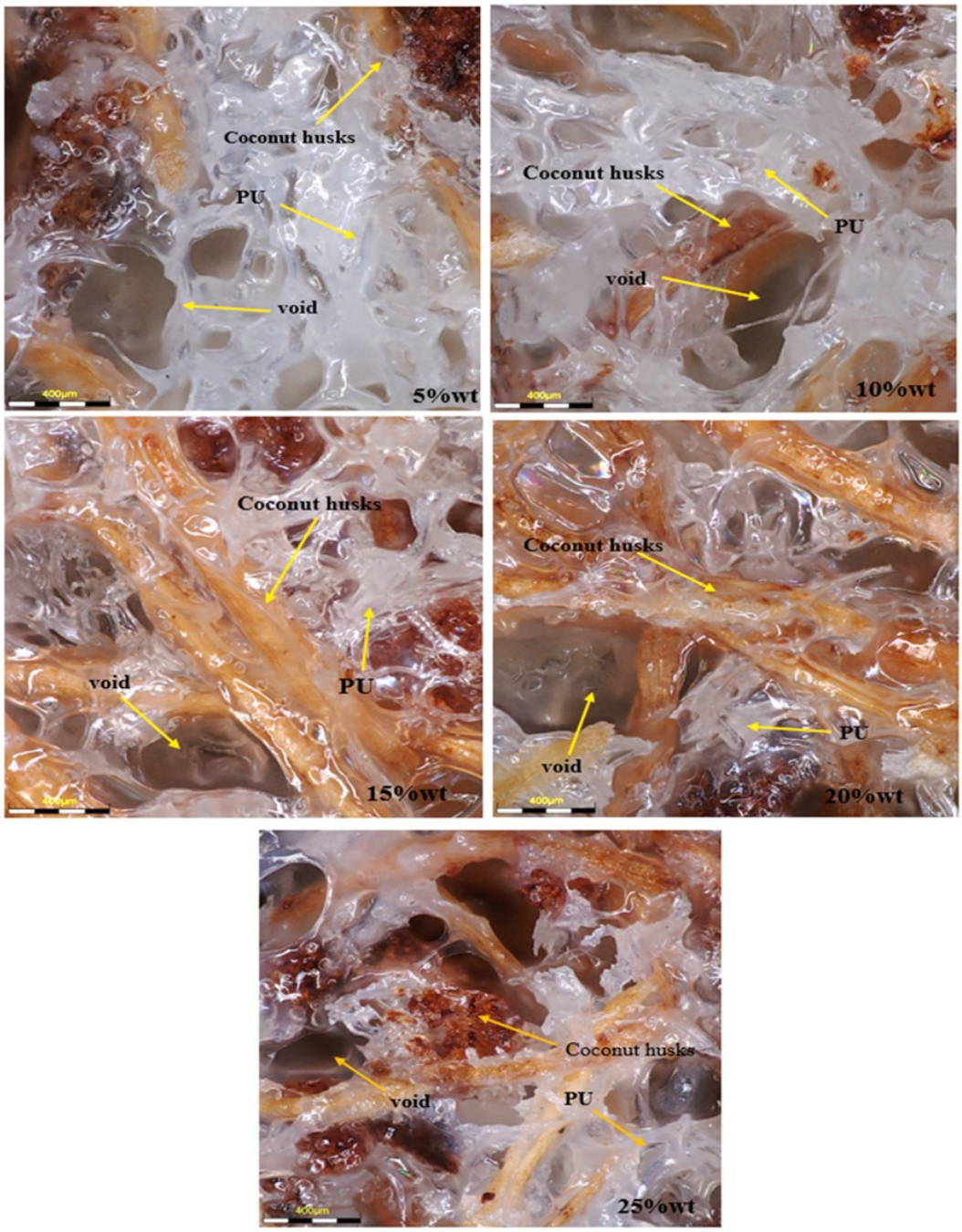

Fig. 13. Digital microscope images of polyurethane composites reinforced with coconut husk at concentrations ranging from 5% to 25% by weight

In addition, optical microscopy images revealed a random distribution of rice and coconut husks within the polyurethane foam, accompanied by partial closure of voids, which contributed to a slight increase in thermal conductivity. This effect became more pronounced at higher reinforcement levels of 20 to 25 wt%, where the increased husk content produced a denser foam structure characterized by reduced void volume and enhanced heat transfer pathways. Furthermore, microscopic images of the rice husk-

reinforced composites showed localized agglomeration of husk particles at low reinforcement levels 5 wt%, which led to greater cell porosity and higher water absorption.

As the reinforcement ratio increased, however, the distribution of the finer and shorter rice husk particles became more uniform within the polyurethane matrix, promoting stronger filler and matrix interactions and reducing both the size and number of open voids. This morphological refinement limited water penetration pathways and improved the composite's resistance to water uptake. This behavior is consistent with the findings reported by Bindir *et al.* (2023). In contrast, the relatively large and coarse structure of the coconut husks enhanced their adhesion to the polyurethane matrix, as evident in the optical microscopy images (Fig.13), facilitating more efficient stress transfer and enabling the composites to withstand higher tensile loads.

Analytic Hierarchy Methodology

By following the steps of the analytical hierarchical process and utilizing Excel formulas, the following results were obtained.

1. The resulting normalized matrix and the corresponding criterion weights are presented in Table 5.
2. Calculation of the Weighted Matrix Score as shown in the Table 6.
3. The ratio of the weighted sum score to the criterion weights (λ_{max}) was calculated, as shown in Table 7.
4. Using Eqs. 4 and 5, the results for Consistency Index (CI) and Consistency Ratio (CR) were 0.038 and 0.042, respectively

Table 5. Normalized Matrix and Calculation of Criteria Weights

Criteria	TC	WA	EB	TS	CW
TC	0.561	0.621	0.547	0.416	0.536
WA	0.186	0.207	0.273	0.25	0.229
EB	0.141	0.103	0.136	0.25	0.158
TS	0.112	0.068	0.045	0.083	0.077

Table 6. Calculation of Weighted Sum Scores

Criteria	TC	WA	EB	TS	WS
TC	0.536	0.687	0.632	0.385	2.24
WA	0.1786	0.229	0.316	0.231	0.9546
EB	0.134	0.1145	0.158	0.231	0.6375
TS	0.1072	0.0763	0.0527	0.077	0.3132

Table 7. The Ratio of the Weighted Sum Scores to the Criterion Weights

Criteria	WS	CW	λ_{max}
TC	2.24	0.536	4.1791
WA	0.9546	0.229	4.1686
EB	0.6375	0.158	4.0348
TS	0.3132	0.0772	4.0675

Since the value of (CR) was 0.042, which is less than 0.1, the criteria weights were considered acceptable.

Method of Additive Ratio Assessments

The evaluation involved four criteria thermal conductivity, water absorption, elongation at break, and tensile stress applied to five alternatives representing reinforcement ratios ranging from 5% to 25% by weight, as follows:

1. Table 8 presents the criteria in four columns, with weights assigned according to test results and the optimal value (OV) identified for each.
2. Table 9 illustrates the normalization of the decision matrix using Eqs. 7 and 8.
3. Table 10 shows function results obtained by multiplying the AHP normalized weights with decision matrix values.

Table 8. Constructing the Decision Matrix for Prepared Composites

Criteria →	TC		WA		EB		TS	
Alternatives ↓	PF_R	PF_C	PF_R	PF_C	PF_R	PF_C	PF_R	PF_C
5 wt%	0.043	0.041	165.5	753	24.32	22.5	0.184	0.2
10 wt%	0.0439	0.042	141.2	670	23.57	20.4	0.197	0.22
15 wt%	0.045	0.0438	129.7	612	17.78	18.6	0.216	0.332
20 wt%	0.0462	0.045	122.2	520	16.9	15.3	0.222	0.662
25 wt%	0.0486	0.046	112.1	460	14.07	13.2	0.226	0.744
	Min		Min		Mix		Mix	
OV	0.043	0.041	112.1	460	24.32	22.5	0.226	0.744

Table 9. Normalized Decision Matrix for Criteria and Alternative

Criteria →	TC		WA		EB		TS	
Alternatives ↓	PF_R	PF_C	PF_R	PF_C	PF_R	PF_C	PF_R	PF_C
5 wt%	0.1739	0.175	0.1289	0.1238	0.2011	0.2	0.1448	0.0689
10 wt%	0.1703	0.1708	0.1511	0.1392	0.1949	0.1813	0.155	0.0758
15 wt%	0.1662	0.1638	0.1645	0.1523	0.147	0.1653	0.1699	0.1144
20 wt%	0.1619	0.1594	0.1746	0.1793	0.1397	0.136	0.1747	0.2281
25 wt%	0.1539	0.156	0.1904	0.2027	0.1163	0.1173	0.1778	0.2564
OV	0.1739	0.175	0.1904	0.2027	0.2011	0.2	0.1778	0.2564

Table 10. Determination of the Optimality Function for Each Alternative

CW →	0.536		0.229		0.158		0.077	
Criteria →	TC		WA		EB		TS	
Alternatives ↓	PF_R	PF_C	PF_R	PF_C	PF_R	PF_C	PF_R	PF_C
5 wt%	0.0932	0.0938	0.0295	0.0284	0.0316	0.0314	0.0111	0.0053
10 wt%	0.0913	0.0916	0.0346	0.0319	0.0306	0.0285	0.0119	0.0058
15 wt%	0.0891	0.0878	0.0377	0.0349	0.0231	0.026	0.0131	0.0088
20 wt%	0.0868	0.0855	0.04	0.041	0.0219	0.0214	0.0135	0.0176
25 wt%	0.0825	0.0836	0.0436	0.0464	0.0183	0.0184	0.0137	0.0197
OV	0.0932	0.0938	0.0436	0.0464	0.0316	0.0314	0.0137	0.0197

4. Table 11 presents the calculation of the optimization value (S_i), which was obtained by summing the criterion values for each alternative horizontally in Table 9. The

Utility degree (K_i) was then determined by dividing the improvement value by the optimal value for each column, as shown in Table 12. Finally, the levels of the alternatives were established based on the K_i results, where the alternative with the highest degree is considered the best for application, as illustrated in Table 12. The results indicate that the 10% wt reinforcement ratio for rice husk compounds and the 25% wt reinforcement ratio for coconut husk compounds are the most suitable among the alternatives for use as thermal insulators for air conditioning pipes.

Table 11. Results of the Optimal Value (*S*i) for Each Alternative

	Criteria									
Alternatives	**TC**		**WA**		**EB**		**TS**		**Si**	
5 wt%	PF_R	PF_C	PF_R	PF_C	PF_R	PF_C	PF_R	PF_C	PF_R	PF_C
10 wt%	0.0932	0.0938	0.0295	0.0284	0.0316	0.0314	0.0111	0.0053	0.1654	0.1589
15 wt%	0.0913	0.0916	0.0346	0.0319	0.0306	0.0285	0.0119	0.0058	0.1684	0.1578
20 wt%	0.0891	0.0878	0.0377	0.0349	0.0231	0.026	0.0131	0.0088	0.163	0.1575
25 wt%	0.0868	0.0855	0.04	0.041	0.0219	0.0214	0.0135	0.0176	0.1622	0.1655
OV	0.0825	0.0836	0.0436	0.0464	0.0183	0.0184	0.0137	0.0197	0.1581	0.1681

Table 12. Showing Ranking Levels for Alternatives

Alternatives	K_i		Ranking	
	PF_R	PF_C	PF_R	PF_C
5 **wt%**	0.9083	0.8306	2	5
10 **wt%**	0.9248	0.8249	1	3
15 **wt%**	0.8951	0.8233	3	4
20 **wt%**	0.8907	0.8651	4	2
25 **wt%**	0.8682	0.8787	5	1

CONCLUSIONS

1. Rice husk and coconut husk reinforced polyurethane composites demonstrated strong potential as sustainable alternatives to conventional insulation materials for air conditioning pipes.
2. The composites exhibited thermal conductivity values ranging from 0.041 to 0.0486 W/m·K, indicating their suitability for thermal insulation applications.
3. At equivalent reinforcement levels, coconut husk composites showed superior mechanical properties compared to rice husk composites, achieving a tensile strength of 0.744 MPa at 25 wt%, which was substantially higher than the 0.226 MPa recorded for rice husk composites.
4. Although coconut husk composites exhibited significant hydrophilicity, increasing the reinforcement ratio reduced water absorption. At 25 wt%, the water absorption ratio decreased to 63.6%, suggesting that reinforcement improved interfacial bonding and limited water uptake.
5. The analytical hierarchy process (AHP) analysis highlighted thermal conductivity as the most critical factor, followed by water absorption, elongation, and tensile stress.

6. According to the additive ratio assessment (ARAS) method, 10 wt% rice husk and 25 wt% coconut husk composites achieved the highest rankings, with ideal degrees of 0.9248 and 0.8787, respectively.

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