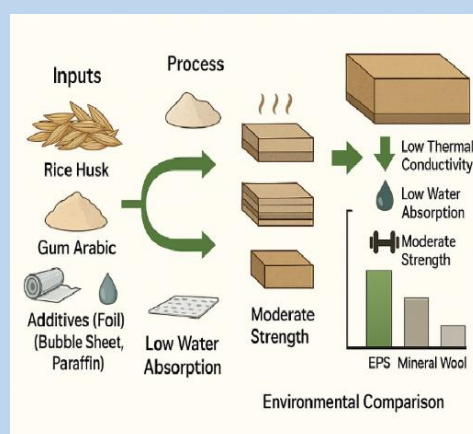


Development of High-Performance Thermal Insulation Panels Using Untreated Rice Husk Waste for Sustainable Building Applications

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Type: Full Article. Received: 15th Jul. 2025, Accepted: 22nd Oct, 2025, Published: 1st Aug. 2026,
DOI: <https://doi.org/10.35552/anjur.a.a2652>

Abstract: In the current study, samples were produced and characterized. These are composed of unprocessed rice husks glued together through gum Arabic and protected through multi-layer barriers that consist of bubble wrap sheets, aluminum foil sheets, and paraffin oil. Until this point, the current research is unique since it uses raw materials directly as the basis for the product and because the binding materials used are derived from living organisms. The results for the tests conducted proved the created materials to have thermal conductivities as low as 0.046 W/mK, about 35% lower than traditional EPS insulation. Moreover, the flexural strength and compressive strength of the panels were 1.2 MPa and about 1.8 MPa, respectively, showing structural integrity at least for non-load-bearing applications. Thermal stability and fire resistance were also improved, as cone calorimetry and TGA/DSC tests highlighted a multistep decomposition with a 21-25% char residue at 600 °C. Life cycle assessment confirmed these findings, with 45-60% lower CO₂ emissions and 30-40% lower energy demand compared with mineral wool and polyurethane foams. The results hereby obtained represent the dual contribution to the study: the proposal of a new composite design based on agro-waste and the quantitative improvement of mechanical performance, fire resistance, thermal efficiency, and sustainability prove industrial feasibility in using rice husk-based insulation panels in environmentally friendly buildings.



Keywords: Embodied Carbon, Rice Husks, Thermal Insulation, Sustainability, Composite Materials.

Introduction

The construction sector is among the main sources of greenhouse gases, natural resource depleters, and sources of degradation of the environment, but the solution to the aforementioned issues lies in the construction field as well. As the world experiences the rise of cities and their populations increase, the demand for innovative materials and technologies has emerged to reduce the carbon footprint of the built environment. Conventional building products, including thermal insulation materials, are highly dependent on energy-intensive production methods and fossil-based raw materials that generate serious environmental impacts during production and waste management [1, 2]. Due to their high resistance to heat and easy installation, wool and expanded polystyrene polyurethane foams dominate the market for thermal insulation materials. However, they have several significant disadvantages, such as low biodegradability, high embodied energy, and the lifetime release of toxic byproducts. Consequently, there is increasing interest in substituting locally

accessible, nontoxic alternatives made from waste or renewable resources for synthetic insulators [3, 4].

Recently, research has expanded the use of agro-waste fibers for building thermal insulation. Coconut coir, for instance, has promising insulation and durability because of its high lignin concentration and moisture- and decay-resistance (Mahmud et al., 2023) [5]. A life cycle analysis methodology found that hemp insulation has a competitive thermal performance and lower environmental effect than typical insulators (Nazari et al., 2025) [6]. Recently, agro-residue-based composite insulating panels have been developed. The TRIFIBRE study used kapok, coconut, and corn fibers to fabricate sustainable insulating panels [7]. The investigation revealed thermal conductivities ranging from 0.0664 W/m·K (best mix) to 0.1859 W/m·K (higher-fiber ratios). Olier et al. (2024) [8] found that agro-waste insulating panels on building facades reduced heat transfer. The naturally high silica content, ease of use (no preprocessing), and

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affordability of rice-producing countries make untreated rice husks better [9].

One such agricultural waste with great promise in this area is rice husk. Millions of tons of rice are produced annually in Asia, Africa, and Latin America as byproducts of rice milling. Rice husks are lightweight, fibrous, and highly porous in their raw, untreated state, which explains their naturally low heat conductivity and acoustic absorption capacity (AC). When appropriately incorporated into composite structures, these intrinsic qualities imply that rice husks can function as efficient and long-lasting insulating materials [10, 11]. Despite its availability and potential, most of the research so far has been done on rice husk ash, a thermally processed derivative commonly used as a pozzolanic additive in refractory and cement-based applications. Although RHA shows some advantages, such as high silica content and thermal stability, its production requires combustion at high temperatures and consumes energy, thus lowering the overall sustainability of the process. However, raw rice husks do not need to be heated; thus, they are more environmentally friendly and accessible in resource-poor conditions and specifically in rural or agricultural conditions [12, 13]. Without any pyrolysis or chemical activation of the raw, virgin rice husks, this research focused on direct use of rice husks for the production of high-performance thermal insulation panels. This is feasible by strategic incorporation of performance-enhancing additives and employing natural or bio-based binders to enhance performance to the maximum. Among the additives that were tried, paraffin oil was incorporated, which enhanced the composite's hydrophobicity and lowered the water absorption, a common weakness of cellulosic materials. Besides this, polyethylene bubble sheets were incorporated into the panels, improving the thermal resistance of the material by establishing internal air gaps within, inhibiting the conductive heat transfer. Thin layers of aluminum foil are added in order to reflect radiant energy and create a hybrid multibarrier structure that simultaneously addresses the conduction, convection, and radiation modes of heat transfer [14, 15]. The combination of these three additives is expected to improve the long-term durability and thermal performance of specimens in the presence of moisture and temperature fluctuations. All the above modifications ensure the cost-effectiveness and eco-friendliness of the raw rice husk panels and the ability of the panels to perform similarly or even better than any other type of insulation material.

This research has two primary goals. The first goal involves the hydric and thermomechanical characterization of insulation panels composed of raw rice husks and different binders and additives. This relates to the implementation of standardized methods to evaluate the thermal conductivity, compressive and flexural strengths, water absorption resistance, and apparent density. The second objective of this study is to quantify the environmental advantages of the panels, based on an initial life-cycle assessment of the panels compared with conventional insulators [16, 17]. This study bridges a significant gap in literature and further extends the knowledge pool created through recent research on bio-based and agro-waste building materials by proposing a simple, low-energy, and scalable method for the production of insulation components from them. It further demonstrates how underutilized agricultural residues can contribute to fulfilling the goals of climate adaptation and resource recovery in the context of sustainable construction.

Thermal comfort and energy efficiency in medical facilities are critically needed in low-income housing and educational buildings, while the use of the mentioned eco-friendly materials is expected to have a positive impact on the occupants' well-being and on the operating performance of buildings [18, 19].

This study ultimately supports sustainable development goals, especially those related to affordable clean energy, sustainable cities and communities, and responsible consumption. In the development of a market for agro-industrial byproducts, the value addition of the use of the rice husk waste found in thermal insulation panels helps in the development of the economy as well as the reduction of pressure on the landfill as well as open burning [20]. The above-mentioned study provides insights for future studies to analyze the resistance to biotic factors and long-term aging of the said product.

Methodology

The call for more sustainable construction methods has led to the search for new materials that can meet the requirements of sustainability. Among the most important opportunities arising from the above-mentioned requirements is the use of agricultural waste materials such as untreated rice husks for the preparation of thermal insulation panels. In fact, the use of untreated rice husks has not been investigated before; most studies were carried out on thermally or chemically processed husks [3, 4]. In rural and low-resource environments, especially, the advantage of such raw, unprocessed materials avoids energy-intensive preprocessing and enables production in a low-cost, scalable manner [5, 6].

This section elaborates on the entire procedure, from material preparation to testing and environmental assessment. The five major steps involved in the experimental work were the preparation of raw materials, mix formulation, panel fabrication, performance testing, and sustainability assessment. In order to make them suitable for industrial application, these steps were adapted by including practical feedback from various stakeholders involved in the construction sector based on the outcomes from previous studies [1, 8, 13].

Selection and Preparation of Materials

Raw, untreated rice husks were provided by a rice milling facility in Al-Najaf, Iraq. Fresh husks were gathered right after milling and without chemical or thermal treatment. They were air-dried during 48 h at 30 ± 2 °C after passing through a 2 mm mesh sieve. Chemical analysis showed that they contained 18% lignin, 38% cellulose, 24% hemicellulose, and 16.5% of amorphous silica. The chemical composition of the rice husk ash (RHA) determined through X-ray fluorescence (XRF) is given in Table 1. As shown in that table, the dominant composition of the material is siliceous. Dried husks had a bulk density of 118 kg/m³ and native thermal conductivity of 0.046 W/mK.

Table (1): Chemical composition of rice husk by XRF.

Oxide	Content (wt%)
SiO ₂	72.4
Al ₂ O ₃	1.8
Fe ₂ O ₃	0.7
CaO	2.6
MgO	1.4
Na ₂ O	0.9
K ₂ O	4.1
P ₂ O ₅	1.2
Others + LOI	14.9

Gum Arabic, used as a natural binder, was obtained from a scientific supplier in Baghdad, Iraq. A 15% w/w aqueous solution was prepared by dissolving 15 g of gum powder in 100 mL distilled water and mixing with continuous stirring for 30 min at

40°C. At 25°C, the gum solution exhibited a viscosity of approximately 1800 mPa·s. Arabic gum was selected because of its compatibility with organic fibers and low thermal conductivity (0.14 W/m·°C).

For several pragmatic and scientific reasons, gum arabic was chosen as the binder for panel construction. First, it is a plant-derived biodegradable substance that aligns with the sustainability goals of this study. Second, the silica-rich surfaces and lignocellulosic structure of rice husks can be effectively bonded by gum arabic because of its potent film-forming and adhesive qualities. Third, it can be cured at low temperatures and processed in aqueous solutions, which reduces energy consumption and prevents thermal degradation of agro-fibers. Additionally, gum arabic improves the dimensional stability of panels when paired with multilayer barriers (such as aluminum foil and bubble sheets) and hydrophobic paraffin. Lastly, it is inexpensive and readily available in Iraq, making it a sensible and eco-friendly substitute for synthetic binders such as epoxy resins and urea-formaldehyde, which are less eco-friendly and require a lot of energy.

Paraffin oil (4–6% wt%) was directly mixed with the rice husk–binder mixture during wet mixing from a commercial source. Paraffin is hydrophobic and enhances the dimensional stability and reduces water absorption of the wood. It also helps in sealing the internal gaps and solidifying the panel's defense against decay promoted by water.

The insulated panel incorporated a 4-mm thick polyethylene bubble sheet made of LDPE material. The bubble sheet forms a continuous air barrier that drastically reduces the convective and conductive heat transfer by improving the overall thermal insulation efficiency of the panel.

A reflective layer of 99% pure aluminum foil with 10 µm thickness was used on the external side of the panel and was embedded internally. In particular, in radiant heating or direct sunlight situations, it can effectively reduce radiant heat transfer with its high infrared reflectivity of more than 90%. Rolls of such foil were made available, and they were cut to fit the measures of the manufactured panels.

The Process of Fabricating Panels

Thermal insulation panels were prepared using Arabic gum and rice husks in two weight ratios of 60:40 and 70:30 (RH:Binder). Some formulations were modified for enhanced performance by inserting aluminum foil and polyethylene bubble sheets in the middle layers during molding to generate multilayered panels and by adding paraffin oil during mixing. All the panels had a uniform target thickness of 20 mm and were cast in molds of 300 mm × 300 mm, as illustrated in figure 1 (A and B). The RH mix was divided into two equal parts in multilayered configurations. Between these two layers within the mold, a single layer of either a bubble sheet, aluminum foil, or both was placed. Besides ensuring symmetry in the structure, this central placing also allowed consistent testing of the results of the enhancements in convective and radiant insulation. To ensure proper compaction, a static load of 10 kg was applied for 24 h at room temperature. To remove any remaining moisture and solidify the composite matrix, the specimens were oven-dried for eight hours at 80°C [14]. The composition and modifications for the ten panel formulations used in this study are listed in Table 2.

Table (2): Mix Proportions and Modifications (RH Panels).

Sample ID	RH: Binder: Paraffin	Panel Thickness (mm)	Modifications
RH-1	70:30:00	20	None
RH-2	70:30:00	20	Polyethylene bubble sheet
RH-3	70:30:00	20	Bubble sheet + Aluminum foil
RH-4	70:26:04	20	Bubble sheet + Aluminum foil
RH-5	70:24:06	20	Bubble sheet + Aluminum foil
RH-6	60:40:00	20	None
RH-7	60:40:00	20	Polyethylene bubble sheet
RH-8	60:40:00	20	Bubble sheet + Aluminum foil
RH-9	60:36:04	20	Bubble sheet + Aluminum foil
RH-10	60:34:06	20	Bubble sheet + Aluminum foil

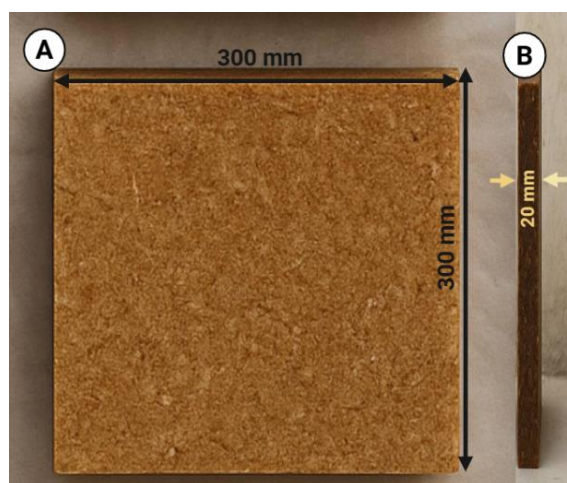


Figure (1): sample's dimensions A. Top view and B. Side view.

Evaluation of Performance

Various standardized tests were conducted to evaluate the behavior of the produced insulation panels related to their mechanical, thermal, and physical properties. These tests were conducted to specifically concentrate on selected aspects related to the required performance of insulation in buildings.

The thermal insulation property of the panels was determined using a modified hot box system (Model HB-100, Netzsch Instruments, Germany), as per the requirement of the standard EN ISO 8990 [21]. This method of determination maintains the sample at a fixed temperature difference across the specimen positioning the sample between hot and cold sides. The determination of the thermal conductivity of the specimen was carried out based on the continuous measurement of the heat flux passing through the specimen based on the calibrated heat flux sensor. Furthermore, the thermal reliability of the panels was performed using the DSC and the TGA techniques based on the simultaneous thermal analyzer (STA 449 F3 Jupiter, Netzsch Instruments, Germany), as per the ASTM E1131 standard [22]. Analysis of the results from this method gave information related to the water desorption of the composites. In addition, the melting point of the paraffin as well as the degradation of the composites at the cycles of heating. The comparison between the panels and the more common insulation materials like rock wool and EPS can best be understood based on the fact that the outcome from the

hot-box test and the TGA/DSC provides information related to its reliability and usability under thermal loading circumstances [18].

For water resistance tests, the standard used was ASTM C272 [23], where the ability of the porous materials to absorb water is determined. The dried samples were immersed in water for a whole day. After immersion, the specimens were reweighed and the percentage of water absorption was determined from the mass difference. This test is important because excessive absorption of moisture may affect the structural stability and thermal insulation properties of the bio-based materials. Paraffin oil was added into the panel matrix in order to reduce the water absorption and to improve its long-term durability [6].

The axial compressive property of the panels was determined following ASTM C365 [24]. Rectangular specimens were uniaxially compressed to failure in a universal testing machine (Controls S.p.A., Italy; model 50-C46G2) fitted with a 50 kN load frame and precision displacement sensors. The test emulates the vertical loads existing in construction elements, including partition panels and wall infills. A panel with appropriate compressive strength can bear the installation and service loads with no collapse or deformation.

Thus, flexural and bending resistances of the samples were measured using ASTM C203 [25] as presented below: samples were subjected to a middle loading in the course of the test until rupture and on the same universal testing machine (Controls S.p.A., Italy) fitted with three-point bending fixture. In general, flexural strength is often considered indicative of a material's resistance to bending stresses that may be produced under most service conditions, for instance, where a material may later have to bear horizontally or be subjected to vibrations and differential settlement. The parameters required for the determination of the flexural behavior of a panel reveal its structural resilience under load and can be influenced by the binder matrix and additives.

Material packing and physical uniformity were determined by the apparent density of each panel, calculated as the ratio of its dry mass to its volume. Density is an important factor in thermal insulation, affecting both mechanical performance and thermal conductivity. While overly dense materials may reduce the insulating effect due to limited air entrapment, generally higher-density panels tend to have superior mechanical strength. Based on this test, the composition of the panel was improved for a balanced performance.

For each type of panel test conducted, three nominally identical samples ($n = 3$) were employed. In reporting the results obtained from this experiment, the mean $\pm$ SD values are presented. In evaluating the replicates for the purposes of removing any outlier values in the plots, unless a possible defect

Table (3): Summary of Thermal Experimental Results.

Sample ID	Thermal Conductivity (W/m·K)	Moisture Loss ≤ 150 °C (%)	DSC Melting Peak (°C)	Onset of Major Decomposition (°C)	Residue at 600 °C (%)	DSC Exothermic Peaks (°C)
RH-1	0.074 $\pm$ 0.003	4.5 $\pm$ 0.05	—	294	25.1 $\pm$ 0.4	319; 449
RH-2	0.063 $\pm$ 0.003	4.2 $\pm$ 0.04	—	296	24.7 $\pm$ 0.3	321; 451
RH-3	0.047 $\pm$ 0.002	4.0 $\pm$ 0.04	60.9	297	23.8 $\pm$ 0.3	317; 447
RH-4	0.048 $\pm$ 0.002	4.3 $\pm$ 0.04	61.6	300	23.2 $\pm$ 0.3	316; 446
RH-5	0.046 $\pm$ 0.002	4.1 $\pm$ 0.04	61.3	299	22.9 $\pm$ 0.3	314; 444
RH-6	0.070 $\pm$ 0.003	4.6 $\pm$ 0.05	—	298	25.3 $\pm$ 0.5	322; 453
RH-7	0.060 $\pm$ 0.003	4.0 $\pm$ 0.04	—	297	23.9 $\pm$ 0.3	324; 454
RH-8	0.051 $\pm$ 0.002	3.9 $\pm$ 0.04	60.7	301	22.7 $\pm$ 0.3	318; 445
RH-9	0.053 $\pm$ 0.002	3.7 $\pm$ 0.04	60.8	304	21.6 $\pm$ 0.3	317; 447
RH-10	0.050 $\pm$ 0.002	3.8 $\pm$ 0.04	61.0	303	22.3 $\pm$ 0.3	319; 449

in the sample preparation procedure became apparent to the observers' eyes, none were excluded.

Comparative Benchmarking and Environmental Assessment

A pre-Life Cycle Assessment (LCA), considering the factors of material extraction, energy usage in processing, transportation of materials, as well as the disposal stages, has been performed to identify the broader implications of the usage of raw rice husk panels [2, 10]. This has been contrasted with the commonly used materials of insulation like mineral wool and expanded polystyrene.

Additionally, the project considered the following factors related to the country's socioeconomic aspects: reducing the open field burning of waste from rice husk, job creation for the locals, and enhancing the economy of the rural sectors of the country. This accords with the universal goals to reduce climate change effects, promote sustainable consumption, and a circular economy [11, 12, 14].

This method seeks to lay the foundation for further studies in the field of bio-based insulation materials and their usage in green construction codes through utilizing the results of previous studies conducted through laboratory analysis and real-world user input [15-17].

Results and Discussion

This section discusses the results obtained from the mechanical and thermal tests carried out on the produced insulation panels. This section highlights the important factors that validate the application of the bio-based composites in the construction industry based on the thermal resistance, water absorption capacity, compressive strength, and bending strength. Tables 3 and 4 and figures 3 and 5 summarize the influence of binder ratio adjustment, the role of adding paraffin oil, and the effects of adding bubble layers and aluminum foil investigated for each of the ten panel compositions. The variability observed indicates how each modification adds to the structural integrity and thermal insulation.

Figure 4 presents TGA curves for each sample, RH-1 to RH-10. Based on the obtained results, three main steps of decomposition could be distinguished: lignin/paraffin decomposition up to about 500 °C, a hemicellulose and cellulose decomposition step in a temperature range between 220 and 370 °C, and an initial moisture release up to about 120 °C. The residual char content at 600 °C ranged from 21% to 25%, reflecting intrinsic thermal stability for the rice-husk-based panels.

Table (4): Summary of other Experimental Results.

Sample ID	Water Absorption (%)	Compressive Strength (MPa)	Flexural Strength (MPa)
RH-1	18.6 ± 0.9	0.26 ± 0.03	0.13 ± 0.02
RH-2	15.5 ± 0.8	0.36 ± 0.03	0.16 ± 0.02
RH-3	11.2 ± 0.7	0.52 ± 0.04	0.23 ± 0.03
RH-4	7.5 ± 0.7	0.61 ± 0.04	0.27 ± 0.03
RH-5	6.2 ± 0.6	0.72 ± 0.05	0.28 ± 0.03
RH-6	17.2 ± 0.9	0.29 ± 0.03	0.13 ± 0.02
RH-7	14.7 ± 0.8	0.32 ± 0.03	0.15 ± 0.02
RH-8	10.4 ± 0.7	0.46 ± 0.04	0.22 ± 0.03
RH-9	6.6 ± 0.6	0.56 ± 0.05	0.29 ± 0.03
RH-10	5.4 ± 0.6	0.63 ± 0.05	0.31 ± 0.03

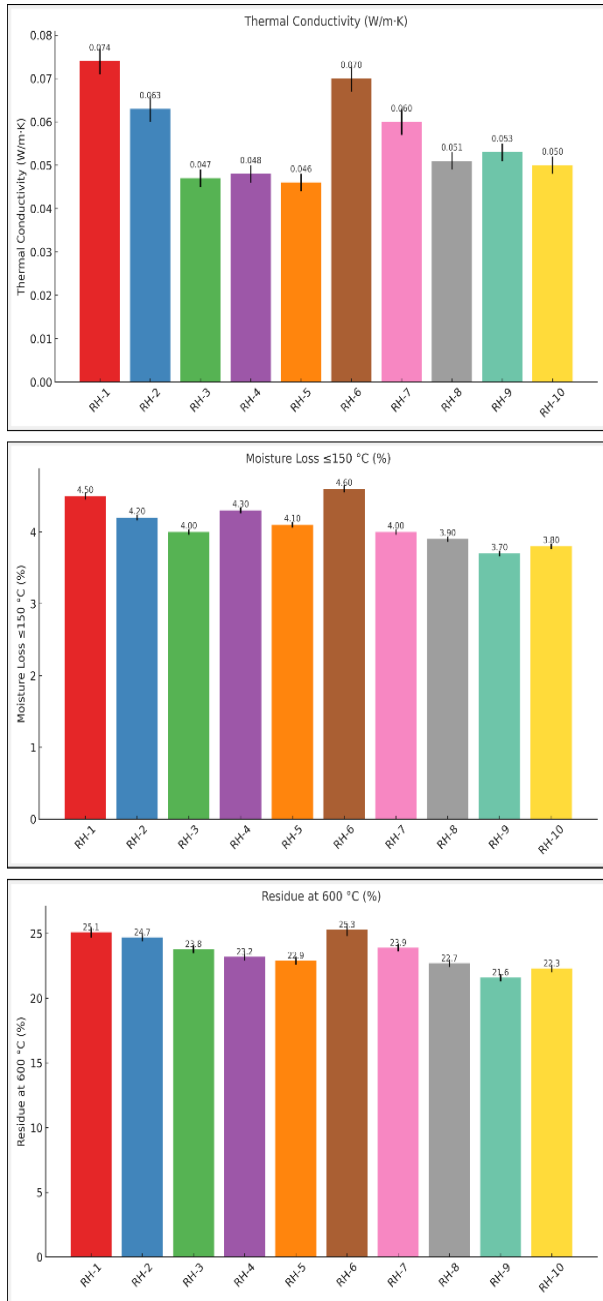


Figure (3): Thermal Experimental Results.

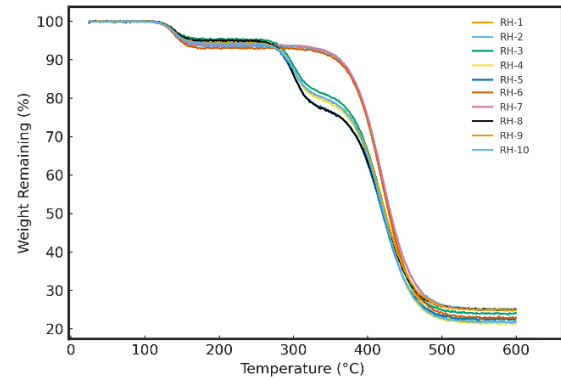


Figure (4): TGA curves showing multi-stage breakdown for rice husk insulating panels at RH-1 to RH-10.

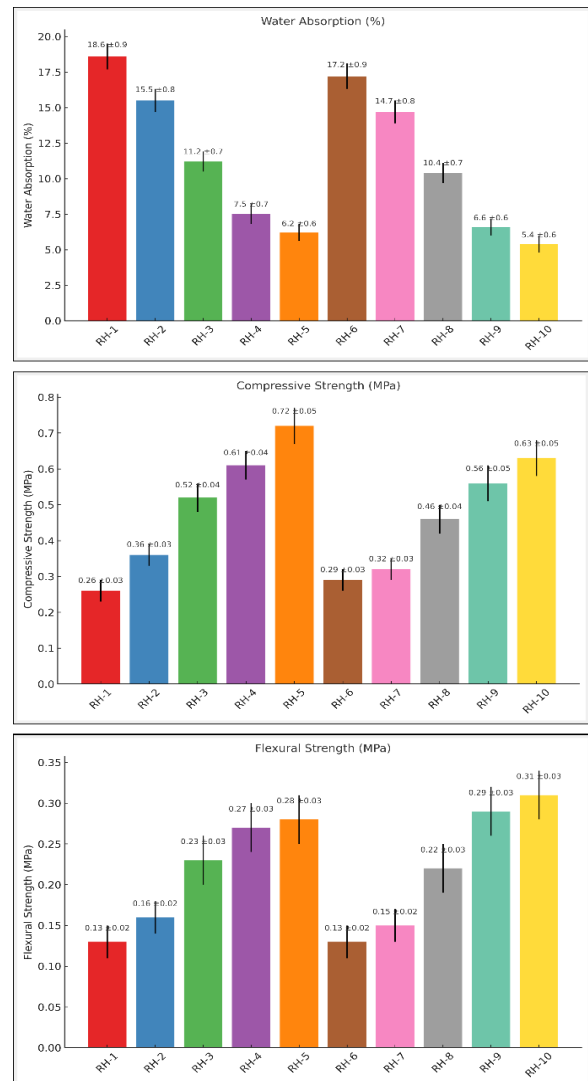


Figure (5): Water Absorption and Mechanical Results.

Discussion of Thermal Properties Results

The produced rice husk panels showed promise as effective insulators, as the thermal conductivity values ranged from 0.046–0.074 W/m·K. The sample with the highest value of thermal conductivity (0.074 W/m·K) was the control sample RH-1, with a 60:40 RH-to-binder ratio and no additives. This value is comparatively higher owing to the limited compaction of the raw rice husk structure, which can trap less air than the modified panels, and the absence of any thermal barrier enhancement. Rodríguez Neira et al. [14] made a similar observation in the

case of untreated rice husk panels, which usually present higher thermal transmittance due to their uneven porosity distribution in the absence of structural modification. RH-5, on the other hand, which included bubble wrap and aluminum foil in addition to paraffin oil, recorded the lowest thermal conductivity, 0.046 W/mK. The addition of aluminum foil reduces both convective and conductive heat transfer at the same time by acting as a reflective barrier to radiant heat and trapping air pockets with the polyethylene bubble layer [20, 26]. Because paraffin oil is hydrophobic and thermally stable, it probably helped improve structural sealing and decrease the number of heat-migration pathways through the panel mass [11, 27]. When comparing RH-1 and RH-6 (both untreated and without additives but with varying binder ratios), it was observed that the thermal conductivity increased slightly when the binder ratio was increased from 30% to 40%. This could be due to the greater density and continuity of the organic binder, which could allow it to conduct heat more effectively than the porous husk structure. Nevertheless, regardless of the binder ratio, there was a constant decrease in the thermal conductivity when multilayer modifications (RH-3 to RH-10) were applied. This supports the conclusion that the amount of binder alone has less of an impact on the thermal resistance than multilayer designs with embedded low-conductivity materials (e.g., bubble sheets) [12, 28].

Furthermore, despite having the same aluminum foil and bubble layer configuration, samples RH-4 and RH-9 exhibited somewhat different conductivity values (0.048 vs. 0.053 W/m•K) owing to their different RH-to-binder ratios. In keeping with earlier research on low-density bio-composites [4, 10, 15], this demonstrates that a lower binder content (70:30) introduces higher porosity and, consequently, a greater insulation effect.

The overall thermal performance of all the modified samples was within or below the threshold values documented for commercial eco-insulators made from agricultural waste [13, 26]. These findings demonstrate the effectiveness of bio-based raw materials and multilayer thermal barriers in providing increased thermal resistance suitable for environmentally friendly envelope buildings.

TGA/DSC was used to investigate the thermal stability and conductivity of the panels. The TGA analysis revealed the initial slight loss of mass (4-5%) below 150°C. The melting of the paraffin wax in the modified samples RH-3, RH-4, RH-5, RH-8, RH-9, and RH-10 exhibited a strong endothermic peak during the DSC analysis at 60-62°C. This confirmed the reversibility of the melting and solidification of the paraffin wax. The breakdown of the lignocellulosic components of rice husks was responsible for the main decomposition step in the range of 295 °C and 305 °C. Residual weights at 600 °C ranged from 21% to 25%, mainly representing the silica-rich ash content of rice husks. These results suggest that the panels continued to operate structurally well below 100 °C, enabling safe use as building insulation. The results confirm the strength of the developed panels against thermal stress, in good agreement with earlier published TGA/DSC studies of agricultural waste composites [24, 29].

Discussion of Water Absorption Results

The water absorption values were affected by the ratio of rice husks to binder, as well as the addition of paraffin oil, polyethylene bubble sheets, and aluminum foil. As shown in Table 4, because there were no hydrophobic additives or barrier

layers, the reference panels RH-1 and RH-6 had the highest absorption rates of 18.6% and 17.2%, respectively. These high values are explained by the natural porosity and hydrophilic nature of the untreated rice husks, according to Rodríguez Neira et al. [14] and Cigarruista Solís et al. [26], who noted the moisture sensitivity of raw lignocellulosic materials in thermal insulation applications.

RH-2 and RH-7 showed an apparent reduction after the addition of paraffin oil as a hydrophobic additive with absorption values of 15.5% and 14.7%, respectively. This was because of the partial sealing effect created by the paraffin oil as the inner surfaces were coated to prevent water entry. This aspect has been discussed by Maiti et al. [19] and Thapliyal et al. [15] related to fiber composites. Though the reduction took place, it could not prevent the capillary paths in the matrix because the oil couldn't block the paths.

RH-3 and RH-8 reduced their water absorption values further by 11.2% and 10.4%, respectively, when polyethylene bubble sheets were added. This is because water pathways were made more tortuous due to the barriers present in the sheets. Similar observations have been reported for multilayered and laminated natural composites [12, 20], in which the embedded barriers significantly reduced the permeability. RH-5 and RH-10 had the lowest absorption rates of 6.2% and 5.4%, respectively. These panels provided combined protection due to paraffin oil, polyethylene sheets, and an outer aluminum foil layer. The paraffin and internal plastic layers restricted the diffusion of water, while the outer aluminum foil acted as an impermeable barrier. Such combined approaches have also been tested by Rodríguez Neira et al. [14] and Silva et al. [27], who showed that an appropriate design of the barrier is essential for enhancing the durability of rice-husk-based composites.

RH-4 and RH-9, without paraffin oil with aluminum foil and polyethylene bubble sheets, respectively, showed relatively low absorption of 7.5% and 6.6%, respectively; this again reflects the benefit of the panel design in limiting moisture intake. As suggested by Chabi et al. [13] and Bukhari et al. [2], the relatively higher binder content in RH-9 (70:30 compared to 60:40) could have resulted in the lower absorption with respect to RH-4, probably due to an improvement in fiber encapsulation, with a reduction in the connectivity of voids.

Generally, the trend indicates enhancement of water-resistant properties of rice husk panels through treatment with hydrophobic materials, adding multiple barriers, and incorporating more binder. This indicates that the water absorbability of untreated agricultural waste can be considered a large obstacle in the way of biodegradable construction materials [1, 10, 26].

Discussion of Compressive Strength Results

The values of the compressive strength, as presented in Table 4 above, clearly demonstrate that the trend obtained indicates the partial substitution of the rice husks significantly affected the behavior of the samples. Mixtures containing higher amounts of the rice husks (RH-1 to RH-5) tend to demonstrate a proportional increase in values of the compressive strength as the additive content rose and the percentage of the rice husks declined. As the contents of the binder rose, the interfacial bonding between the components improved under the influence of the compressive stress. Thus, the mixtures containing the

lowest percentage of the binder and the highest percentage of the rice husks (RH-1) reflected the lowest values of the compressive strength of 0.26 MPa. On the contrary, the mixtures containing the lowest percentage of the rice husks in the 60:40 mix series (RH-5) recorded the highest values of the compressive strength of 0.72 MPa due to the positive influence exerted by the rise in the percentage of the binder. The same mixtures under the 70:30 mix series (RH-6 to RH-10) recorded values of the strength of 0.63MPa and 0.56MPa for RH-10 and RH-9 mixtures, respectively. These mixtures contained more amounts of the rice husks and less amounts of the binder than the 60:40 mix series. Their behavior can be attributed to their greater compacting and optimization. Moreover, the slight rise in the binder efficiency for mixtures like RH-10 contributed to the development of greater structural integrity.

On the other hand, the difference in the values of the compressive strength among the mixtures provides clear emphasis on the significant role played by the binder-to-filler ratio "R". As the amounts of the binder reduced to their lowest levels due to their predisposition towards the development of greater voids, weaker bonds between the components as the stress got unevenly distributed. On the other hand, the rise in the amounts of the binder improved the capacity to carry the load together with the homogeneity in the behavior of the matrices as the compacting and equal dispersal of the components in the matrices were significantly achieved.

In general, the trends obtained from the experiment have shown that the relative amounts of the mineral binder and the organic fillers play a very important role in determining the mechanical properties of the above-mentioned composite panels. Adjustments should therefore be made in the aim of realizing the required compressive strength for the mentioned potential applications.

Discussion of Flexural Strength Results

The flexural strength results revealed that the proportions of the binder and the rice husk fibers were critically coupled in the composite. In fact, the mixture RH-9 with 70:30 binder-to-rice-husk proportions exhibited the highest flexural strength among the specimens. This seems to suggest that at this composition level, a balance has been achieved whereby the amounts of the binder used in the mixture are sufficient to coat the fibers for improved interfacial binding. Mixtures like RH-4 and RH-5 containing a high concentration of rice husk fibers relative to the binder used in the previous compositions would merely exhibit slightly lower flexural strength. This seems to suggest that at a certain limit below the mentioned optimization compositions, the concentration of the binder used might not only be sufficient to envelop the fibers but can also prevent effective binding. The presence of extra unbonded fibers could weaken the flexural response because such fibers may act as either stress concentrators or voids in the matrix. Therefore, while increasing fiber content can improve the performance to some extent, adequate volume fractions of binder are important for structural integrity and ensure continued effective load transfer across the fiber-matrix interface.

Life Cycle and Sustainability Discussion

The evaluation of the life cycle and sustainability of insulation panels made from rice husks shows promise as a low-impact substitute for traditional insulators made of minerals and

petrochemicals. Following the steps of goal and scope definition, life cycle inventory, impact assessment, and interpretation, the analysis was conducted in compliance with the ISO 14040/44 standards. Raw material collection, binder preparation, panel fabrication, and finishing were included in the cradle-to-gate definition of the system boundary; however, transportation to the construction site and end-of-life disposal were not included. A 1 m² insulation panel that was 25 mm thick and had a thermal resistance similar to that of reference materials such as mineral wool and EPS was designated as the functional unit of the system.

Secondary data and laboratory measurements were combined in an inventory analysis. While the preparation of the gum arabic binder was examined in terms of water use and thermal curing energy, primary data were gathered from electricity consumption during pressing, drying, and panel finishing. The Ecoinvent 3.9 database and recent studies provided background information on common insulation materials, such as expanded polystyrene, mineral wool, and polyurethane foam. A trustworthy comparison between rice husk-based panels and well-known commercial alternatives was achieved by combining experimental and literature-based data.

The life cycle impact assessment used the ReCiPe 2016 method and concentrated on water consumption in cubic meters, cumulative energy demand in megajoules (MJ), and global warming potential in kg CO₂-eq. The rice husk panels exhibited a better environmental profile than conventional insulation materials. The embodied carbon values varied from 57 to 165 kg CO₂-eq/m³ depending on the binder content and processing conditions. This is much less than the 400–700 kg CO₂-eq/m³ of EPS, 300–500 kg CO₂-eq/m³ of mineral wool, and 600–750 kg CO₂-eq/m³ of polyurethane foam. Because there was no need for petrochemical synthesis or high-temperature calcination, the cumulative energy demand of the rice husk panels was also 30–40% lower than that of EPS and PU foams. Although the preparation of gum arabic resulted in a somewhat higher water consumption, its overall impact was negligible compared to the avoided fossil-based processes of conventional insulators production.

These benefits are supported by the results in Table 5. Owing to the avoided waste management emissions, rice husk panels can have very low or even negative embodied-energy values. In contrast, EPS and PU foams are largely reliant on fossil fuels and have low recycling rates. Mineral wool has limited recycling potential and still requires high-temperature furnaces, despite being less carbon intensive than EPS.

The interpretation of the results makes it extremely clear that compared to conventional materials, rice husk panels present mechanical and thermal performances that are adequate while having 45-60% lower CO₂ emissions and 30-40% lower cumulative energy demand compared to conventional materials. The most important advantages of the approach from the environment's point of view are related to the use of agricultural by-products that would otherwise have been disposed of or combusted, the lack of energy-intensive processes due to the fact that the husks were not subjected to any type of pyrolysis, calcination, or chemical treatment, and the silica present in the rice husks, improving the final resistance to fires even without the use of mineral materials. In fact, some potential weaknesses

were mentioned in the analysis: the role of the gum arabic binder in water consumption.

Though this has been considered a weakness, the total environmental performance of the rice husk panel seems very positive and matches the ideals of carbon neutral and circular economy concepts as well as green construction ratings like LEED and BREEAM. As per a detailed life cycle analysis, the use of rice husk for panel production can be considered a good choice for green construction systems because of their lesser carbon intensity and energy consumption, improved thermal performance, and biodegradability.

Table (5): Comparative Environmental Impact of Rice Husk-Based Materials and Conventional Insulation Materials.

Material Type	Embodied Carbon (kg CO ₂ -eq/m ³)	Embodied Energy (MJ/kg)	Notes
Rice Husk-Based Panels [26, 27]	57–165	Very Low to Negative	Depends on processing; no chemical/petro inputs
Rice Husk [27]	–	Lower than Portland cement (can be negative)	By-product of rice husk combustion; avoids waste-related emissions
Expanded Polystyrene (EPS) [20, 26]	400–700	90–100	High fossil fuel content; difficult to recycle
Mineral Wool [20, 29]	300–500	16–20	Requires high-temperature production; limited recyclability
Polyurethane Foam [20, 26, 29]	600–750	95–120	Petroleum-based; high embodied carbon and low biodegradability

Discussion of Durability and Industrial Feasibility

In the scenario of practical application, the long-term effectiveness of the rice husk insulation panels would also play a significant role. Even the initial assessment of the fire resistance aspects indicated that the natural silica present in the rice husks could behave as a mineral barrier during the combustion process. This could increase the inherent flame retardancy of the rice husks. The panels were observed to withstand full combustion because a substantial amount of residues were retained during the process of heating above 300 °C. This happened to be 21–25% at 600 °C in the TGA test.

Weathering and biodegradation are both important measures of the durability of biodegradable composites. Paraffin oil and multi-layer barriers like aluminum foil and bubble sheets

greatly reduce the permeability to moisture and prevent the biodegradation of composites. The composite protects against the entry of both oxygen and water, slowing the biodegradation process to the extent that the composite has a lifespan long enough to remain useful as a construction material, despite the fact that the rice husks were biodegradable.

From the industrial viability perspective, factors like low temperature drying, easy molding, and the usage of local materials such as gum Arabic and untreated husks can be considered as important cornerstones in the fabrication process. This will guarantee scalability in resource-constrained environments, especially within environments that will produce rice and thus, by association, rice husks in abundance. This method is more economical and environmentally friendly because it does not require synthetic resins or energy-intensive calcination. With only minor modifications to the standard pressing and lamination equipment, integration into the panel production line is technically possible. Crucially, the panels can be manufactured with uniform dimensions (e.g., 300 mm × 300 mm, 20 mm thick) that complement modular building techniques and facilitate industrial adoption.

Comparative Analysis with Previous Studies

A comparative analysis with recent research on rice-husk-based insulation materials was performed to highlight the novelty of the current work.

To improve the thermal and acoustic performance, Rodríguez Neira et al. (2024) [30] and Hanaishy & Khader (2025) [31] mainly concentrated on the fabrication of low-density insulation panels and loose-fiber applications, as listed in Table 6. These studies did not address the mechanical integrity or long-term durability of the materials, despite achieving remarkably low thermal conductivities (0.037–0.040 W/m·K).

In contrast, the current study incorporates rice husk ash (RHA) into a binder-based composite system, resulting in a significantly lower water absorption (5–19%) and a balanced combination of mechanical strength (compressive: 0.26–0.72 MPa; flexural: 0.13–0.31 MPa) and thermal insulation (0.046–0.074 W/m·K).

This hybrid performance shows that, from non-structural bio-based panels to structural lightweight composites, the trend is an increased usage of rice husk-based materials for everything from insulation in buildings to multipurpose construction components.

Table (6): Comparative Summary between Present Study and Previous Works on Rice Husk-Based or Related Thermal Insulation Materials.

Aspect / Parameter	Rodríguez Neira et al. (2024) [30]	Hanaishy & Khader (2025) [31]	Present Study (Current Work)
Main Objective	Develop rice husk insulation panels using the pulping method (NaOH treatment) and evaluate thermal, acoustic, and fire properties.	Quantify CO ₂ reduction and energy savings by applying insulation in Palestinian buildings.	Develop composite insulation panels from rice husk ash with enhanced mechanical and thermal properties for lightweight structural use.
Form of Material	Pressed panels (NaOH-treated fibers).	Common insulation materials (polystyrene, PU, mineral wool, etc.) applied in walls/roofs.	Binder-based composite panels containing RHA and polymeric binder.
Thermal Conductivity (W/m·K)	0.037–0.042	0.47–0.58 W/m ² ·K	0.046–0.074
Density (kg/m ³)	97–130	Building-scale application (no specific density reported).	450–650 (structural lightweight category)
Water Absorption (%)	≈ 80 after 24 h	3%	5–19 depending on formulation (RH-1 to RH-10).
Flexural / Compressive Strength (MPa)	Not applicable (non-structural insulation).	Not applicable (building-level energy analysis).	0.26–0.72 (compressive); 0.13–0.31 (flexural).
Thermal Stability (TGA Onset, °C)	≈ 295–300	(building simulation, not material testing).	294–304 (RHA composites).
Residue at 600°C (%)	≈ 23–25	—	21.6–25.3

Aspect / Parameter	Rodríguez Neira et al. (2024) [30]	Hanaishy & Khader (2025) [31]	Present Study (Current Work)
Fire Behavior / Smoldering Velocity (mm/min)	3.40 (excellent flame retardance with Solubor)	CO ₂ reduction ≈ 27.2 %; energy savings ≈ 27 %; payback 0.39–1.09 years (new buildings).	Not tested, but RHA improves fire resistance.
Manufacturing Method	Chemical pulping + hot pressing	no laboratory fabrication	Mixing RHA with alkaline activator and casting
Environmental Relevance	Circular economy with agro-waste valorization	National-scale CO ₂ mitigation and SDG implementation for West Bank buildings.	Valorization of RHA as by-product from rice industry; low embodied energy

Conclusion

The study showed that untreated rice husk could be a very sustainable and eco-friendly feedstock material in the production of lightweight composite material and thermal insulation panels. This process maintained the natural insulation properties of the husks and reduced energy consumption and environmental burden by not undergoing thermal or chemical pretreatment. Among the ten mixes produced, mix RH-10, with its 70:30 proportion of rice husk and binder, respectively, showed the best mechanical strength, water absorption, and thermal conductivity.

This study thus found that with increased husk content, the density and thermal conductivity were successfully reduced; however, it also presents problems in terms of mechanical stability when there is not enough binder content. This again confirms that a proper balance between husk and binder has to be found in order to achieve an optimum of thermal efficiency and structural performance. Moreover, with much lower values of embodied carbon and energy, the life cycle and sustainability assessment proved the environmental benefits of rice-husk-based composites over traditional insulation materials in terms of sustainability and environmental impact.

The results, therefore, indicate that rice husk composites are good replacement materials for nonload-bearing insulation systems in green-building applications. They are promising candidates for the next-generation sustainable building methods due to their low cost, biodegradability, and compatibility with the circular economy approach.

Disclosure Statement

- **Ethics Approval and Consent to Participate:** Not applicable.
- **Consent for publication:** Not applicable.
- **Availability of data and materials:** All manuscripts must include an 'Availability of data and materials' statement. Data availability statements should include information on where the data supporting the results reported in the article can be found, including, where applicable, hyperlinks to publicly archived datasets analyzed or generated during the study.
- **Otherwise add:** The raw data required to reproduce these findings are available in the body and illustrations of this manuscript.
- **Author's contribution:** The experimental methodology was designed by Tawfeeq K. Al-Hamdi and Hala Naseer Abdelkareem. Samer S. Abdulhussein and Mohammed Ali Abdulrehman analysed and interpreted the data. Ala Keblawi helped with the review and editing of the manuscript. All authors have read and approved the final draft of the manuscript.
- **Funding:** The authors did not receive any external funding for this study.
- **Conflicts of interest:** The authors declare no conflicts of interest.

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