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Original

# Development of Cellulose–Rice Husk Composite: Evaluation of Fire Resistance and Fungal Growth

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**Abstract:** This study examines the use of recycled materials in sustainable construction, specifically a rice husk-newspaper-PVAc-borax composite made from recycled newspaper cellulose (9%), rice husk (14%), borax (15%), and polyvinyl acetate-PVAc (62%). Tests for water absorption, density, fire resistance, and mold growth were conducted following ASTM and European standards. The composite showed high water absorption but improved moisture resistance due to rice husk and borax. Its intermediate density balances strength and lightness, making it suitable for various applications. Fire tests revealed reduced fire propagation in samples containing borax, enhancing fireproofing properties. Borax also inhibited fungal growth, aligning with previous studies. While these results are promising, further research is needed to evaluate the composite's commercial viability and performance.

*Keywords:* **cellulose, rice husk waste, fire resistance, fungal growth, natural fibers**

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## 1. Introduction

Polymer composites reinforced with natural fibers have emerged as attractive alternatives in material science due to their reduced environmental footprint during production and end-of-life disposal. A substantial portion of the natural fibers used in these systems are derived from agro-industrial residues, making them both sustainable and cost-effective (Ben Hadj Tahar et al., 2024; Ghalme et al., 2025; I. Singh et al., 2025). Although natural fiber-reinforced composites do not match the mechanical performance of glass fiber-reinforced plastics (GFRPs), they offer distinct advantages, such as low thermal conductivity, biodegradability under natural conditions, and effective sound insulation properties (Ben Hadj Tahar et al., 2024).

Thermal insulators are characterized by their high resistance to heat flow, which limits the transfer of thermal energy between regions with different temperatures. For a material to qualify as an effective insulator, its thermal conductivity must remain below 0.08 W/m·K (Cengel & Ghajar, 2020). Complementary parameters, such as vapor diffusion resistance, moisture uptake, water content, thermal transmittance (U-value), and resistance to mechanical stresses (tensile, compressive, and flexural), mold proliferation, and fire exposure, must also be considered (Marín-Calvo et al., 2023; Quintaliani et al., 2022). Flame retardancy describes a material's behavior under fire conditions, while antifungal performance is evaluated through tests that assess the effectiveness of additives such as borax in suppressing microbial growth (Cao et al., 2025; Gairola et al., 2025; Xu et al., 2025).

Efficient insulation materials are essential for thermal regulation in the transport and storage of sensitive goods, for protecting electronic components from overheating, and for building energy efficiency (Gonzalez-Serrud et al., 2022; González-Serrud et al., 2024). Notably, space conditioning accounts for over 10% of global energy consumption, reinforcing the urgency for bio-based insulators as a viable pathway toward climate mitigation strategies (Alyami, 2024).

Historically, bio-based materials such as wood chips and recycled paper were common in insulation applications before the advent of petroleum-derived polymeric foams. However, their insulation performance was generally limited (Lu et al., 2024). In recent years, renewed interest in thermal insulation materials of biological origin has gained momentum as part of global efforts to reduce the environmental burden of synthetic insulators (Mazur et al., 2025). Cellulose-rich materials, such as recycled newspaper, have exhibited notable thermal insulation properties and have been widely used for this purpose since the early 20th century, particularly across North America and Europe (Vėjelis et al., 2024). Other lignocellulosic residues—such as rice husk, coconut fiber, and paper waste—have shown promise for thermal insulation applications due to their favorable thermal conductivity values (Akhter et al., 2025). For instance, agricultural residues from Morocco blended with cardboard waste have been evaluated, yielding thermal conductivity values ranging from 0.072 to 0.098 W/m·K, depending on the specific composition (Benallel et al., 2024).

A comprehensive review of cellulose fiber insulation reported average thermal conductivity values of approximately 0.040 W/m·K, although these can vary depending on the source of the cellulose and the processing methods employed (Benallel et al., 2024).

Water absorption is a critical factor affecting insulation efficiency, as excessive moisture uptake can degrade thermal performance and encourage fungal growth (Dahal et al., 2023). In the study by Penjumras et al. (2015) (Penjumras et al., 2015), all tested composites absorbed more than 40% water after 24 hours of immersion, underscoring the importance of incorporating hydrophobic properties into insulation materials. Among the fibers evaluated, rice husk composites exhibited the lowest water absorption rate (42%), outperforming those reinforced with wood (63%) and textiles (60%). This enhanced performance is attributed to the unique microstructure and lower porosity of rice husk fibers (Muthuraj et al., 2019).

Density is also a key parameter, closely linked to the material's porosity, mechanical integrity, and heat transfer properties (Di Canto et al., 2023) (Muthuraj et al., 2019) reported low-density composites (378–488 kg/m$^3$), values comparable to those of natural fiberboards made from wheat husk or sugarcane bagasse. The thermal conductivity of porous materials results from a combination of conduction through the solid matrix and convective heat transfer through the gas-filled pores, making pore structure a decisive factor in insulation efficiency (Koru, 2016).

To improve fire performance, natural fiber composites often require the addition of flame retardants. Borax, a boron-derived compound, is widely used for this purpose due to its dual role in suppressing both combustion and microbial proliferation (Sejdinović, 2022). Dosages in the range of 15–20% by weight are generally recommended, with enhanced performance observed when used in

conjunction with boric acid. (Lopez Hurtado et al., 2016). Boron has shown sporicidal activity against several fungal species, even under conditions of elevated humidity. Fire resistance testing of hemp-based composites per EN ISO 11925-2 confirmed delayed ignition and improved flame resistance compared to conventional materials, further supporting the role of bio-composites in fire-safe construction (Rocha et al., 2024).

In response to the construction sector's high energy demand and considerable carbon emissions, there is a growing trend toward replacing petroleum-derived insulation materials with renewable, environmentally sustainable alternatives (Carlos Javier et al., 2023). Natural fibers and recycled materials such as rice husk and cellulose from newsprint have garnered attention due to their availability, affordability, and environmental advantages (Pal et al., 2021). In previous research by our group (Marín-Calvo et al., 2023), a composite made from newspaper (14%), rice husk (9%), borax (15%), and polyvinyl acetate glue (62%) demonstrated promising thermal conductivity (0.042 W/m·K), alongside tensile and compressive strengths of 1.74 MPa and 20.5 MPa, respectively.

Building on these findings, the present study aims to assess the water absorption capacity, bulk density, fungal resistance, and flame retardancy of the developed composite at the laboratory scale. This research is conducted within the framework of sustainable materials development in Panama, where substantial quantities of rice husk waste—estimated at around 15,000 tons annually from approximately 87,060 hectares—are discarded. These figures underscore the urgent need for innovative materials that valorize local agro-industrial residues while offering environmentally responsible alternatives to conventional insulation products (Benallel et al., 2024).

### *1.1 Contribution to Sustainable Construction*

The use of agro-industrial residues such as rice husk and industrial waste like shredded newspaper in the composite formulation supports the sustainability goals of the construction sector within a circular economy framework (Chikhi et al., 2013). Materials traditionally considered waste are valorized as functional raw inputs, reducing dependence on virgin resources and lowering the amount of waste sent to landfills or incineration (Agüero et al., 2020).

Their incorporation also decreases the carbon footprint of construction materials by partially replacing synthetic, high-impact components. Lignocellulosic fibers such as rice husk provide thermal, mechanical, and biodegradable benefits, contributing to energy efficiency and reduced environmental impact at end-of-life (Munar et al., 2025).

The environmental footprint of the rice husk–newspaper–polyvinyl acetate–borax composite is generally lower than that of conventional insulation materials due to its reliance on recycled and renewable feedstocks and the reduced use of petroleum-based polymers (Asdrubali et al., 2015; Korjenic et al., 2011). Production requires relatively low energy compared with synthetic foams like polyurethane or polystyrene, which involve energy-intensive polymerization and blowing agents (Papadopoulos, 2005; Pargana et al., 2014). At end-of-life, cellulose-based components provide partial biodegradability, while the non-toxic nature of borax enables safer degradation compared with flame-retardant additives in conventional foams that may release persistent pollutants (Khan et al., 2025). Although polyvinyl acetate is not fully biodegradable, the overall formulation reduces landfill burden and environmental persistence relative to petroleum-derived foams or mineral wool, which demand energy-intensive recycling or disposal (Milat et al., 2025).

These features position the composite as an environmentally favorable alternative, especially for applications emphasizing sustainability, circularity, and a reduced ecological footprint (Marín-Calvo et al., 2023).

## 2. Materials and Methods

### *2.1 Materials*

The following materials were used to prepare the different specimens (see Table 1): Shredded newspaper (from Panamanian newspapers), ground rice husk (supplied by Cooperativa de Ahorro y Crédito El Avance. R. L. Los Santos, Panama), polyvinyl acetate (Grip Bond 2); borax (20 Mule Team Borax), as antiseptic and fire retardant. The instruments and equipment used include molds for the creation of density, water absorption, flammability, and fungal growth test tubes; digital balance (5000 g capacity, accuracy of 0.004 oz., Bonvoisin CO., China), vernier (Total tools CO., PTE. LTD., China), mortar mixer (16 inches in length, 2.5-inch mixing head, Ion Tool CO. China), stove (Frigilux Rim Inox, Venezuela), distilled water, chemical beaker, swabs and Simplantes (Fungal and yeast counts, SIMPLATE CO., United States).

Energy dispersive X-ray fluorescence analysis was conducted at the Smithsonian Institution in Panama. Field emission scanning electron microscopy (FESEM) was performed using a ZEISS EVO 40 from Oxford Instruments (Abingdon, United Kingdom). A thin layer of

a gold-palladium alloy was sputtered onto the surfaces using an EMITECH sputter coating, SC7620, from Quorum Technologies Ltd. (East Sussex, UK) to ensure conductivity. The elemental composition of the materials used for the new composite material was as follows:

Table 1. Energy-Dispersive X-Ray Spectroscopy (EDS).

| Shredded newsprint | | | Rice husk | | |
|---|---|---|---|---|---|
| Element | # at | [wt.%] | Element | # at | [wt.%] |
| Hydrogen | 1 | 4.962 | Hydrogen | 1 | 3.289 |
| Carbon | 6 | 65.516 | Carbon | 6 | 20.048 |
| Oxygen | 8 | 27.363 | Oxygen | 8 | 42.807 |
| Aluminium | 13 | 1.400 | Nitrogen | 13 | 0.567 |
| Calcium | 20 | 0.759 | Silicium | 14 | 33.289 |
| White glue (Grip Bond 2) | | | Borax (20 Mule Team Borax) | | |
| Hydrogen | 1 | 5.670 | Hydrogen | 1 | 25.436 |
| Carbon | 6 | 63.329 | Boron | 5 | 10.079 |
| Oxygen | 8 | 31.001 | Oxygen | 8 | 52.792 |
| | | | Sodium | 11 | 11.692 |

### 2.2 Methodology for Composite Samples

To fabricate the composite material, the rice husk was initially ground and sieved through a 0.6 mm mesh to ensure uniform particle size. Husk particles larger than 0.6 mm were reground until they passed through the mesh. Once the appropriate particle size was achieved, the required proportions of ground rice husk, shredded newspaper, and borax were weighed using a precision balance. The dry components were mixed using a mortar and pestle mixer to ensure an initial uniform distribution. Subsequently, polyvinyl acetate-based glue (Grip Bond 2) was added to the mixture as a binding agent. The complete mixture was further homogenized using a mechanical mortar mixer until a consistent and cohesive mass was obtained.

The homogenized mixture was immediately transferred into molds of defined geometry. After molding, the samples were left to dry under ambient conditions until fully solidified. Once dried, the composite specimens were carefully demolded and prepared for subsequent physical, thermal, and microbiological characterization (Gonzalez-Serrud et al., 2023; Marín-Calvo et al., 2023).

The composite formulation used in this study—comprising 9% rice husk, 14% shredded newspaper, 15% borax, and 62% polyvinyl acetate-based adhesive by mass—was selected based on a previous experimental study by the same research group (Marín-Calvo et al., 2023). In that work, three different formulations were evaluated, all containing a constant amount of borax and adhesive, while varying the proportions of rice husk and newspaper. Compositions with a higher proportion of rice husk (>10%) showed increased porosity but resulted in reduced mechanical strength and higher variability in density, which compromised material integrity. Conversely, mixtures with lower rice husk content (<8%) presented improved compaction but exhibited reduced thermal resistance. For the cellulose fraction, increasing shredded newspaper above 15% led to higher water absorption and dimensional instability, while reducing it below 12% negatively affected thermal conductivity. Similarly, the borax content was optimized at 15%, since lower levels (<10%) provided insufficient fire resistance, whereas higher proportions adversely affected mechanical properties due to reduced binder availability.

Regarding the binder, polyvinyl acetate concentrations below 60% produced composites that were brittle and prone to cracking, while increasing the binder content above 65% reduced thermal performance because of the denser polymeric matrix (Ergun et al., 2023). Thus, the chosen composition represented an optimal balance, yielding the best compromise between thermal insulation (0.042 W/m·K), mechanical strength (tensile: 1.74 MPa; compressive: 20.5 MPa), and material stability. These values refer to previous work by the authors (Marín-Calvo et al., 2023), in which the rice husk–newspaper–PVAc–borax composite was characterized for its thermal and mechanical performances (see Table 2). This study represents a second phase of investigation, focusing on additional material properties, including water absorption, flammability, and microbial resistance, rather than generating new thermal conductivity data. The inclusion of these complementary evaluations provides a more comprehensive assessment of the composite's suitability for sustainable building applications.

Table 2. Summary of thermal conductivity and mechanical performance of composite formulations with varying rice husk and newspaper content (Marín-Calvo et al., 2023).

| | Thermal Conductivity (W/m·K) | Tensile Stress (MPa) | Compressive Stress (MPa) |
|---|---|---|---|
| Composition 1 | 0.0409 | 1.74 | 20.23 |
| Composition 2 | 0.0452 | 1.31 | 20.19 |
| Composition 3 | 0.0461 | 1.76 | 20.19 |

### 2.3 Antimicrobial and Flame-Retardant Mechanisms of Borax

The multifunctional role of borax (sodium tetraborate decahydrate, $Na_2B_4O_7{\cdot}10H_2O$) in the developed composite material is attributed to its dual action as both an antimicrobial agent and a flame retardant, governed by distinct but complementary mechanisms (Cavdar et al., 2015). From a microbiological standpoint, borax disrupts microbial viability through osmotic stress—by increasing the ionic strength of the surrounding environment—thereby impairing homeostasis in fungal and bacterial cells, leading to dehydration and metabolic inhibition. Furthermore, borate ions interfere with enzymatic pathways, particularly those involving cis-diol-containing cofactors such as $NAD^+$, which are essential to energy metabolism (Ceylan et al., 2025). This biochemical interference is compounded by the ability of borax to alter membrane permeability via phospholipid interactions and to raise the local pH to mildly alkaline conditions, both of which hinder microbial adhesion, spore germination, and proliferation. These synergistic effects are consistent with the substantial reduction in colony-forming units (CFUs) observed in borax-treated samples (Soytürk et al., 2023). In parallel, borax imparts flame retardancy through thermochemical transformations. Upon heating, it undergoes endothermic dehydration, absorbing heat and releasing water vapor that dilutes combustible volatiles and displaces oxygen near the composite surface (Wang & Shi, 2026). Continued exposure to heat leads to the formation of a boron-rich, glassy char layer (primarily $B_2O_3$), which acts as a barrier to heat and mass transfer, stabilizing the polymer matrix and inhibiting the release of flammable gases. Additionally, borate compounds may scavenge free radicals (H• and OH•) involved in flame propagation. Collectively, these phenomena contribute to the composite's enhanced resistance to microbial attack and reduced flammability, reinforcing its suitability for applications in humid and fire-prone environments (Liu, 2022).

Borax (sodium tetraborate) is generally regarded as low in toxicity, and when embedded in the polyvinyl acetate (PVAc) matrix of the composite, its mobility and potential exposure are minimal under normal residential or commercial use (Chantaramanee et al., 2025). Safety assessments, such as those from the Cosmetic Ingredient Review, indicate that borax is safe in consumer products at concentrations below 5%. In this study, borax represents about 15% of the formulation but is immobilized within a solid adhesive matrix, not intended for dermal contact or ingestion (Writer, 2024). Standard precautions during fabrication—gloves, masks, and adequate ventilation—are recommended to minimize inhalation or skin contact with the powder (Cavdar et al., 2015). With proper handling and installation, borax effectively contributes to fire retardancy and microbial resistance without posing significant health risks (Gairola et al., 2025).

### 2.4 Water Absorption

According to (Chen et al., 2018) and ASTM C 1763 (ASTM International, 2020), after the three specimens (1" high and 2" in diameter) are fabricated. The specimens must be dried in an air oven at 105 °C for 4 hours. Subsequently, the samples are weighed using a balance with an accuracy of four decimals. The samples are placed in a room with 65% of relative humidity (RH) at 25 °C. The specimens are immersed in a chemical beaker with distilled water (300 milliliters) and kept at room temperature for 24 hours. The specimens are drained for 10 minutes. The samples are reweighed. Three specimens were made to perform three water absorption tests, and the mean value was calculated. After the material is submerged in water for 24 hours, part of the material dissolves, which is why replicas cannot be made from the same sample.

$$\%\text{ofwaterabsorption} = \frac{M_h - M_s}{M_s} \times 100\% \quad (1)$$

Where,

$M_h$ = mass of the sample after exposure to moisture.

$M_s$ = mass of the dry sample.

### 2.5. Density Test

According to ASTM C-303 (ASTM International, 2021), to obtain the density, the mass should be determined using a precision balance. Subsequently, fill a chemical beaker with water and then introduce the specimen, apply Archimedes' physical principle, and thus obtain the volume of the specimen. To characterize the density of the material, specimens of 1" high and 2" in diameter were used. This is because it complies with the adequate measures to be introduced into the chemical vessel.

### 2.6. Flammability Test

According to the state of the art consulted (Day & Wiles, 1978; Dogan et al., 2021; Gairola et al., 2025; Liu, 2022; Moreno et al., 2021; Sprague & Shen, 1979), it has been established that borax has fire-retardant properties. The present test was carried out with the objective of verifying the effectiveness of borax as a flame-retardant agent in the developed composite material. Three specimens (1" high and 2" in diameter) were fabricated using the composite material without adding borax to the mixture, and another three specimens were created by adding borax.

In Figure 3, the methodology to be followed for performing the flammability test is shown. A "frigilux Rim Inox" stove was used, then the burner and the metal cover were removed. Subsequently, the stove was set to the lowest power setting, and the test sample was placed in the flask for five minutes. The flask is removed from the oven. Finally, a visual inspection is performed and compared with different samples with and without borax.

In addition to the European standard UNE 23-725 (Asociación de Normalización Española, 1990), there are several other recognized standards for performing flammability tests on materials. Although these tests were not carried out in this study, it is important to mention them to provide a complete overview of the regulatory landscape in this field.

The ASTM D635 standard (ASTM International, 2003; Muktha & Gowda, 2017). This standard describes a method for evaluating the flammability of polymeric materials by measuring the rate of flame spread over the surface of a material exposed to a controlled ignition source.

Another relevant standard is ISO 5660 (Hwang et al., 2023). This standard describes a procedure for determining the flammability and smoke characteristics of materials by measuring heat generation and gas production during exposure to an ignition source. In addition, the UL 94 standard (Guo et al., 2017), developed by Underwriters Laboratories, is widely used to evaluate the flammability of plastics and composite materials. This standard classifies materials into different flammability categories according to their ability to extinguish flame and resist ignition.

### *2.7 Fungi Growth Test*

Similarly, three specimens were fabricated using the composite material without adding borax to the mixture, and another three specimens were created by adding borax to the mixture. All six specimens were exposed to a fungal growth solution, completely covering their surface.

The "AOAC Official Method 2002.11 - Simplate technique for enumeration of fungi and yeasts" (Feldsine et al., 2003) was used and the steps to be followed were as follows: A representative sample of the composite material was taken and transferred to a sterile container. Serial dilutions of the original sample were prepared to obtain manageable concentrations of microorganisms. A suitable sterile culture medium was prepared for fungal and yeast growth. A Simplate plate and a sterile swab were used to apply the diluted sample to the surface of the plate. The procedure was repeated with different dilutions and samples using fresh Simplate plates. The plates

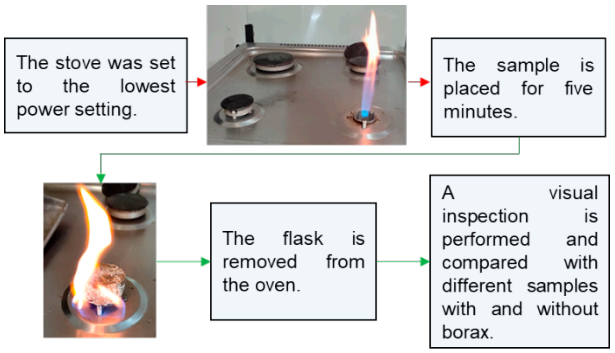



Figure 1. Methodology to be followed to perform the flammability test.

were incubated in an incubator according to the required conditions. After incubation, the fungal and yeast colonies present on each plate were examined and counted. Colony enumeration results are recorded for each sample and dilution (D, $10^{-1}$, $10^{-2}$) (Feldsine et al., 2003).

The Simplate Technique for enumeration of fungi and yeasts, according to AOAC 2002.11 method, is a total enumeration technique that does not focus on identifying specific species of fungi and yeasts. Instead, it is used to determine the presence and total amount of these microorganisms in the sample analyzed. The objective of this study was to evaluate the answer of the composite with and without borax to the general presence of fungi and yeasts.

## 3. Results and Discussion

### *3.1. Water Absorption*

Table 3, presented below, compiles the dry mass and wet mass data of three replicates (S1, S2, and S3) of the composition detailed in the methodology (rice husk 9%, newspaper 14%, 15% borax and 62% of polyvinyl acetate). From these data, the percentage of water absorption is calculated. Additionally, an average value is provided, reflecting the average absorption of the samples tested.

Table 3. Data needed to obtain the average water absorption.

| | Dry mass (g) | Wet mass (g) | Water absorption (%) |
|---|---|---|---|
| S1 | 23.98 | 39.72 | 65.63 |
| S2 | 33.76 | 58.67 | 73.77 |
| S3 | 31.00 | 51.08 | 64.79 |
| | | Average | 68.06 ± 5 |

Sample S2 shows the highest percentage of water absorption (73.77%), followed by sample S1 (65.63%) and sample S3 (64.79%). This variability in the results may be due to several reasons, such as possible fluctuations in the environmental conditions during the test or variations in the internal structure of the samples.

The difference in the composition of the samples, because of the manufacturing process (small variations in the proportion of constituent materials), may have contributed to the observed disparities in water absorption levels. For example, the presence of different amounts of polyvinyl acetate, borax, or the distribution of cellulose and rice husk fibers could influence the ability of the samples to absorb water.

Comparing the water absorption capacity of the manufactured material (9% rice husk, 14% newsprint, 15% borax and 62% polyvinyl acetate), with the absorption capacity of other materials reported in the literature, such as cardboard, newsprint, egg trays, Ecovio (composites reinforced with rice and wheat husks), as well as textile and wood fibers. Ecovio emerges as a leading polymeric material in the search for sustainable alternatives to conventional plastics (Muthuraj et al., 2019). Ecovio's manufacturing process is based on renewable raw materials, such as corn starch and polylactic acid (PLA), making it an environmentally friendly option. The results reported in the literature for Ecovio composites reinforced with rice husks exhibited the lowest water absorption, with an average value of 43%. On the other hand, materials reinforced with wood fibers showed the highest water absorption, with an average of 65%. These variations in water absorption can be attributed to differences in the structure and chemical composition of the raw materials used (Muthuraj et al., 2019).

Paper-based materials, such as cardboard, wastepaper, and newsprint, exhibited extremely high levels of water absorption, with values more than 300%. This finding underlines the importance of considering moisture resistance when selecting materials for specific applications (Noor et al., 2019).

Additionally, the fabricated composite for the present study consisting of shredded newspaper, ground rice husk, polyvinyl acetate (Grip Bond 2), and borax (20 Mule Team Borax), showed a water absorption capacity of 68.06%. This indicates an intermediate performance in terms of moisture resistance compared to other materials presented in the reviewed literature.

Comparing the percentage of water absorption in natural and recycled insulating materials mentioned in the reviewed literature (Muthuraj et al., 2019; Noor et al., 2019) with the developed composite, it was found to have an average water absorption (68.06%). This value is higher than other materials specifically designed to prevent water absorption, such as wheat husk/Ecovio and rice husk/Ecovio, with 43% (Muthuraj et al., 2019). The developed composite is prone to absorb a significant amount of water when exposed to humid conditions. However, the incorporation of rice husk and borax may provide benefits such as improved moisture resistance compared to other cellulose insulators, which may be advantageous in specific climates (Kumar et al., 2024). The water absorption exhibited by the proposed composite may indicate that it is susceptible to damage and deformation when exposed to wet conditions. Although despite the, the studied composite compared to materials such as used paper and egg tray, it absorbs 4 times less water (Noor et al., 2019).

The heterogeneity in water absorption observed among samples S1–S3 was mainly linked to microstructural differences from fabrication, including bulk density, fiber size distribution, binder-to-fiber ratio, borax dispersion, curing conditions, and specimen preparation effects. These factors influenced porosity and permeability, resulting in variability in water uptake (Muktha & Gowda, 2017). Such inconsistencies can be mitigated through process optimization, including standardized fiber drying and sizing, corrected polyvinyl acetate additions, homogeneous mixing and compaction, controlled curing, and uniform specimen trimming and conditioning. Reporting absorption normalized to density further improves reproducibility (Mohammed et al., 2023).

Water absorption of the rice husk–newspaper–PVAc–borax composite can also be reduced by incorporating hydrophobic additives (e.g., silane, siloxane, wax emulsions, nano-clays), modifying cellulose fibers (acetylation or esterification), or applying surface coatings with waterproof resins or polymeric films (Bang et al., 2024). These strategies, applied individually or in combination, improve interfacial bonding, reduce hydrophilicity, and enhance durability in humid environments without compromising mechanical performance (Puneethraj et al., 2025; Ramos et al., 2025; Wang et al., 2024).

### 3.2. Density Test

Table 4 shows the results obtained from three replicates (S1, S2, and S3) of the composition mentioned in the methodology (rice husk 9%, newspaper 14%, borax 15%, and polyvinyl acetate 62%).

Sample S2 exhibited the highest measured density at 0.72 g/cm$^3$, followed by sample S1 (0.64 g/cm$^3$) and

Table 4. Data needed to obtain the average density.

| | Mass (grams) | Volume 1 (mL) | Volume 2 (mL) | Density (g/mL) |
|---|---|---|---|---|
| S1 | 38.18778 | 200 | 260 | 0.64 |
| S2 | 34.67762 | 200 | 248 | 0.72 |
| S3 | 27.58828 | 200 | 245 | 0.61 |
| | | | Average | 0.66 ± 0.06 |

sample S3 (0.61 g/cm$^3$). These differences in density may stem from variations in the distribution and concentration of the constituent materials, as well as the presence of internal porosities or structural inconsistencies formed during the fabrication process.

Density plays a critical role in the evaluation of material performance, particularly in engineering applications where the mass-to-volume ratio directly affects both mechanical behavior and end-use functionality. For this reason, the density of the developed composite was benchmarked against various polymeric and natural reference materials.

A wide spectrum of densities was observed across the compared materials. Among polymers, low-density polyurethane (~0.040 g/cm$^3$) has been reported in specialized biobased foam formulations achieving ultralight structures (Yang et al., 2021). Low-density polyethylene (~0.92 g/cm$^3$) and high-density polyethylene (~0.98 g/cm$^3$) fall within their typical ranges for structural and packaging applications (Lazaro-Hdez et al., 2025). In contrast, natural materials such as cork exhibit significantly lower densities—air-dried cork typically ranges from about 0.12 to 0.24 g/cm$^3$ (Muthuraj et al., 2019)—and wool felt or filter wool shows bulk densities around 0.20 g/cm$^3$, reflecting their highly porous structure (Milat et al., 2025). Inversely, denser materials like wood average approximately 0.60–0.90 g/cm$^3$ depending on species, with many common hardwoods (e.g., maple, ash, cherry) around 0.84 g/cm$^3$ (Ross, 2010), indicating a more compact internal structure with greater mass per volume. Natural rubber also registers a relatively high density of ~0.91 g/cm$^3$, which contributes to its mechanical strength and durability (Hamed, 2011) (Gent, 2005).

The composite material developed in this study, comprising shredded newspaper, ground rice husk, polyvinyl acetate (Grip Bond 2), and borax, achieved a measured density of 0.66 g/cm$^3$. This intermediate density reflects a well-integrated structure with a balanced distribution of both fibrous and polymeric components. Compared to conventional high-density polymers such as silicone rubber, PEHD, and PELD, the proposed composite exhibits a notably lower density, which could be advantageous in lightweight applications (thermal insulation, false wall, case) (Rocha et al., 2024). Conversely, the material demonstrates a higher density than low-density natural alternatives like cork, fiberglass, and foamed polyurethanes, which is indicative of a more compact and robust configuration. Nevertheless, its density remains below that of wood-based materials, suggesting a favorable compromise between weight and structural integrity (Muthuraj et al., 2019).

### 3.3. Flammability Test

Figures 2 and 3 show the photographs of the six specimens (3 specimens without borax and 3 specimens with borax) after performing the flammability test.

The incorporation of borax into the composite formulation was found to markedly enhance its fire resistance compared to specimens manufactured without this additive. Experimental observations revealed that composites containing borax exhibited limited flame spread and only superficial surface degradation. In contrast, samples devoid of borax experienced extensive fire propagation, leading to deeper structural damage and overall reduced fire resistance performance. These findings underscore the role of borax as an effective flame-retardant agent within the composite matrix. Consequently, its inclusion is particularly advantageous in applications where the

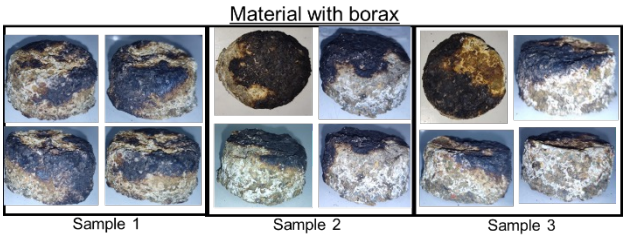



Figure 2A. Results in the specimens of the composite material with borax.

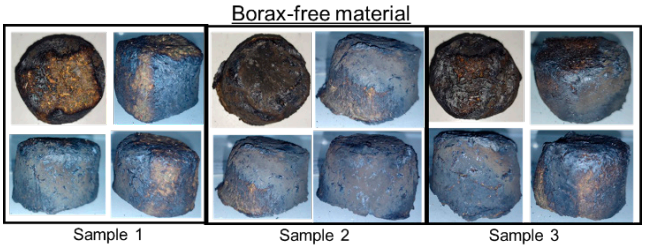



Figure 3. Results in the specimens of the composite material without borax.

material may be exposed to ignition sources, such as in the construction of buildings, transportation components, and electronic enclosures.

For quantitative evaluation, parameters such as flame spread rate or ignition time are needed to yield more reliable and reproducible conclusions about the fire performance of a material. These measurements, obtained through standardized tests like the cone calorimeter (ISO 5660 / ASTM E1354), ASTM E84/ISO 5659 surface burning tests, or UL 94 vertical/horizontal burn tests, provide objective data on ignition, heat release, mass loss, and smoke production, enabling comparison between formulations and correlation with material properties. In this study, the flammability test was performed visually, which provided preliminary indications that the samples were moderately resistant to ignition and flame propagation (Dogan et al., 2021; Gairola et al., 2025; Yiga et al., 2021; Zhang et al., 2023). These observations are consistent with the presence of borax in the composition, which is known to enhance fire retardancy by promoting char formation and slowing combustion, although quantitative testing would be required to confirm and accurately compare this effect (Wang & Shi, 2026).

### 3.4. Fungi Growth Test

Table 5 shows the results of the Simplate technique performed on three samples with borax and three samples without borax.

Table 5. Results of the growth assay using the Simplate Technique for enumeration of fungi and yeasts.

| Material with borax | P | C | D | Fungi and yeast count (UFC/mL) |
|---|---|---|---|---|
| S1 | 0 | <1 | 1 | <1 * |
| S2 | 0 | <1 | $10^{-1}$ | <1* |
| S3 | 0 | <1 | $10^{-2}$ | <1* |
| Borax-free material | | | | |
| S1 | 84 | <738 | 1 | < 730 ** |
| S2 | 84 | <738 | $10^{-1}$ | <7380 ** |
| S3 | 84 | <738 | $10^{-2}$ | <73 800 ** |

No. of positive wells (P)
Most Probable Number of Colony Forming Units per Plate (C)
Dilution Factor (D)
Colony Forming Unit (CFU)
* There was no microbial growth in the three dilutions performed (D, $10^{-1}$, $10^{-2}$).
** There was microbial growth in all 3 dilutions. (D, $10^{-1}$, $10^{-2}$); the limit of detection of microorganisms is higher than that of the technique used.

The fungal and yeast counts for samples of material with borax and without borax, in different test tubes and dilutions. In the samples of material with borax, it is observed that there was no microbial growth in the three dilutions performed (D, $10^{-1}$, $10^{-2}$), indicated by «<1» or «<1» or «<1» Colony Forming Units (CFU) per mL. This suggests that the presence of borax in the material may have an inhibitory effect on the growth of fungi and yeasts.

In contrast, in samples of material without borax, a significant growth of fungi and yeasts was observed at all dilutions. The CFU counts per mL are higher, indicating a higher concentration of microorganisms compared to the samples of material with borax.

It is important to note that the detection limit of microorganisms for this technique is higher than the technique used in this study. This means that it is possible that the CFU counts are underestimated and that the actual presence of fungi and yeasts is higher than reported (only for the case of samples without borax).

Overall, these results suggest that the presence of borax in the composite material may have an inhibitory effect on the growth of fungi and yeasts. However, it is necessary to consider that these results were obtained using a specific technique and that there could be differences in the sensitivity and specificity of other microbiological counting techniques.

These findings are consistent with previous research that has pointed out the antimicrobial potential of borax (Herrera, 2005; Lopez Hurtado et al., 2016; Wu et al., 2022). However, additional studies are required to better understand the exact mechanisms of inhibition and to evaluate the safety and efficacy of the composite material in relation to microbial growth.

Borax (sodium tetraborate) inhibits microbial proliferation through multiple mechanisms. It disrupts fungal cell membrane integrity, alters membrane permeability, and interferes with enzymatic activity critical for energy metabolism and cell wall synthesis (Yu et al., 2025). Borax also chelates essential metal ions such as calcium and magnesium, which are required for spore germination and hyphal growth, thereby limiting fungal development (Gairola et al., 2025). Additionally, it can induce osmotic stress within microbial cells, further reducing their ability to grow and colonize the composite material. These combined effects contribute to the observed reduction in fungal growth in borax-containing samples, enhancing the durability and bio-resistance of the composite (Chantaramanee et al., 2025; Liu, 2022).

The method used, the Simplate technique for enumeration of fungi and yeasts according to the official AOAC

2002.11 method, is a total enumeration technique that does not focus on identifying specific species of fungi and yeasts. Instead, it is used to determine the presence and total amount of these microorganisms in the sample analyzed (Feldsine et al., 2003). Since our objective was to evaluate composite behavior with and without borax to the general presence of fungi and yeasts, to obtain a total count, rather than to identify individual species.

### 3.5. Comparison with Other Bio-based Insulating Materials

The formulation developed in this study exhibits a thermal conductivity of 0.041 W/m·K, a value previously reported by the same research group (Marín-Calvo et al., 2023) in a comparative assessment involving other bio-based insulating materials. In that study, several thermal insulators made from natural fibers or recycled materials were evaluated, yielding the following results: coconut fiber: 0.025 W/m·K; rice straw: 0.050 W/m·K; rice husk (untreated): 0.073 W/m·K; and the composite made from newspaper, rice husk, borax, and PVAc: 0.041 W/m·K.

These values position the proposed composite as an intermediate solution, offering a balanced combination of thermal insulation performance, raw material availability, and ease of processing. While it does not reach the lowest conductivity observed (as in the case of coconut fiber), its formulation provides additional functional benefits, such as resistance to microbial growth and flame retardancy, attributed to the incorporation of borax.

Moreover, its density and structural cohesion, enhanced by the PVAc binder, make it well-suited for applications requiring a certain degree of stiffness or mechanical integrity, such as interior claddings, partition walls, or non-load-bearing prefabricated panels.

The rice husk–newspaper–PVAc–borax composite demonstrates competitive thermal insulation performance compared with other bio-based materials. Reported thermal conductivity values include hemp-based insulation (0.055–0.065 W/m·K, depending on density and compression) (Fiedler & Pedersen, 2025), coconut fiber insulation (≈0.05 W/m·K at 120 kg/m$^3$) (Akhter et al., 2025), and wheat husk insulation (0.031–0.036 W/m·K, comparable to conventional insulators) (Barbieri et al., 2020; Muthuraj et al., 2019). The rice husk–newspaper–PVAc–borax composite exhibits values between 0.0409 and 0.04607 W/m·K, indicating performance on par with or superior to these alternatives.

Beyond its thermal properties, the composite offers advantages such as lower manufacturing costs, reliance on recycled raw materials, and reduced need for specialized processing, supporting scalability for large-scale applications. It is primarily suited for building and construction, including thermal insulation panels for walls, roofs, and partitions in residential, commercial, and industrial structures (Guo et al., 2021; Vidal et al., 2023). Additional applications include prefabricated modules, acoustic insulation, and lightweight construction elements. While laboratory tests confirm promising thermal, mechanical, and durability performance, field studies under variable conditions of temperature, humidity, and environmental stressors are needed to validate long-term service life (Dahiya et al., 2020; Jiang et al., 2021).

The incorporation of agro-industrial residues such as rice husk aligns with sustainability and circular economy goals. It reduces reliance on non-renewable resources, lowers the environmental footprint of material production, and diverts agricultural waste from landfills or burning, thereby mitigating greenhouse gas emissions. Converting rice husk into insulation panels supports energy-efficient construction while fostering innovation in sustainable material design and promoting environmentally responsible practices (Marín-Calvo et al., 2023).

### 3.6. Limitations and Future Research

This study provides results on the antifungal and fire-resistant behavior of a bio-based rice husk–newspaper–PVAc–borax composite; however, several limitations must be addressed.

First, the long-term durability of the material under realistic service conditions—including cyclic moisture, elevated temperature, UV radiation, and microbial exposure—remains untested (Das et al., 2025; Murad et al., 2025; Shettigar et al., 2025). Preliminary evaluations suggest moderate resistance to water uptake and limited microbial colonization due to borax and PVAc hydrophobicity, but systematic accelerated aging studies are required to assess degradation, dimensional stability, mechanical retention, and fire performance over time.

Second, only qualitative flammability observations were performed. Future work should include quantitative testing (e.g., flame spread rate, ignition time) to validate fire performance (Murad et al., 2025). Similarly, antifungal evaluation relied on visual inspection; more sensitive techniques such as plate counting, ATP bioluminescence, qPCR, or CLSM would allow precise quantification of microbial load, growth rates, and inhibition efficacy (Liu et al., 2023; Rintala et al., 2025; Singh et al., 2026).

From a manufacturing standpoint, semi-manual fabrication introduced variability in fiber distribution, compaction, and curing. Scaling up requires standardization of

component ratios, mechanical mixing for homogeneous dispersion, controlled pressing, and consistent conditioning protocols (Das et al., 2025; Morsy et al., 2025). Pilot-scale trials using calibrated molds and monitored curing have shown reproducibility improvements (Murad et al., 2025; Neu & Kuhlicke, 2026; Shettigar et al., 2025).

Economic analysis indicates that the composite is cost-competitive, with estimated manufacturing costs of \$150–\$200/$m^3$, compared with polyurethane (\$300–\$400/$m^3$) and polystyrene foams (\$250–\$350/$m^3$) (Pulidindi & Ahuja, 2025). Cost advantages arise from recycled feedstocks and modest PVAc/borax usage (Marín-Calvo et al., 2023), although regional material availability and labor costs must be considered. Comprehensive life cycle and cost–benefit analyses will clarify commercial viability.

Future studies will also explore strategies to reduce hydrophilicity, such as biodegradable hydrophobic coatings, silane or siloxane coupling agents, nano-clays, or fiber modifications (acetylation, esterification). While borax enhances fire resistance and microbial inhibition, its content must be optimized to preserve flexibility and mechanical integrity (Wang et al., 2025). Long-term exposure risks, even with borax immobilized in PVAc, will be assessed for regulatory compliance and user safety.

Finally, field-scale applications are recommended to validate performance in building assemblies under real conditions. Research priorities include:

- Accelerated durability and fatigue testing,
- Enhanced water and microbial resistance through additives or treatments,
- Optimization of fiber dispersion, binder alternatives, and scalable processing,
- Comparative life cycle and market analyses versus conventional and bio-based insulators.

These steps will help establish the composite's technical reliability, environmental benefits, and commercial competitiveness for sustainable construction.

## Conclusions

The experimental composite exhibits a moderate susceptibility to water uptake, which could lead to structural degradation and dimensional instability under prolonged exposure to moisture. Nevertheless, it demonstrates a significantly lower water absorption—approximately four times less—than traditional cellulosic materials like recycled paper or egg cartons. The synergistic inclusion of rice husk and borax appears to enhance its hydrophobicity, contributing to superior moisture resistance relative to other cellulose-based thermal insulators.

From a physical standpoint, the composite's density, measured at 0.66 ± 0.06 g/mL, falls within an intermediate range compared to standard polymeric and organic materials. This property is particularly relevant for engineering applications that necessitate an optimal compromise between mechanical robustness and material lightweighting—such as structural components in construction or portable thermal barriers. Interestingly, this density exceeds that of many conventional water-repellent insulators, suggesting improved mechanical stability without a significant weight penalty.

The integration of borax into the composite matrix introduces multifunctional benefits. Beyond acting as a flame-retardant additive by forming a thermal barrier under heat exposure, borax also imparts antifungal and antimicrobial properties. Microbiological analyses confirm that borax effectively suppresses fungal and yeast proliferation, an aspect crucial for maintaining the material's integrity in humid or biologically active environments. These attributes not only broaden the composite's functional profile but also open pathways for its adoption in thermal and sanitary insulation systems.

Overall, the developed material combines intermediate water absorption and density levels with enhanced fire and biological resistance, making it a strong candidate for applications in sectors such as sustainable construction, lightweight polymeric components, and environmentally conscious packaging. The valorization of agro-industrial residues like rice husk within this composite underlines the feasibility of circular manufacturing practices in our region. Such research supports the development of bio-based, locally sourced alternatives that reduce dependency on environmentally detrimental synthetic materials, fostering a sustainable and innovative materials economy.

## Conflict of Interest

The authors have no conflict of interest to declare

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