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Assessment of Elaboration and Performance of Rice Husk-Based Thermal Insulation Material for Building Applications

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Abstract: Developing environmentally friendly building materials with low environmental impacts is receiving more attention nowadays to face the global challenges of climate change; building insulation materials made from agricultural waste can be used for their low environmental impact and to generate responsible supplies that utilize natural resources adequately. The study aims to assess a panel made from rice husk using the pulping method. An experimental design established the proportion of rice husk, the percentage of additive (NaOH concentration), boiling time and blending time. Taguchi's method was applied to investigate the effect on density and thermal conductivity; the final panel with optimum conditions was morphologically analyzed using scanning electron microscopy (SEM); the thermal behavior was studied by thermogravimetric analysis (TGA); fire reaction and smoldering behavior were analyzed; and characterization in water absorption and acoustic absorption performances were established. The results show thermal conductivity values between 0.037 and 0.042 W/mK, a smoldering velocity of 3.40 mm/min, and a good acoustic absorption coefficient in octave frequency bands between 125 Hz and 4 kHz greater than 0.7. These characteristics are competitive with other insulating bio-based materials available on the market. This study employed chemicals utilized by other biomaterials for the pulping process and in flame retardants. However, it is important to investigate natural treatments or those with a diminished environmental impact.

Keywords: bio-insulation material; pulping method; Taguchi method; smoldering; fire behavior; rice husk

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1. Introduction

The construction industry consumes 40% of material resources, 25% of water and 35% of energy worldwide; it also generates over 25% of solid waste and 38% of greenhouse gases [1]. This sector is responsible for reducing finite resources, and much of their environmental impact comes from the combustion of fossil fuels. Therefore, it is essential to reduce greenhouse gas emissions by using environmentally sustainable building materials [2]; the development of building materials from sustainable sources to reduce the use of petrol-based products is being investigated in different applications [3]. Furthermore, considering the use of locally available raw materials from environmentally friendly renewable or recycled sources to make construction materials is essential from the perspective of sustainable development [4] and for their contribution to achieving the sustainable development goals [5]. Several studies report different solutions for building materials that are fabricated using natural fibers and low-technology methods to comply with contemporary comfort standards, making them a great alternative to be adapted for industrial use [4]. Agro-waste is a sustainable alternative for the building sector because it is a commercial and technically feasible solution to propose eco-friendly building construction materials [6].

Protecting the envelope of a building with insulation measures is the best means of improvement to achieve comfort and energy savings the low thermal conductivity and fibrous character of the majority of vegetal fiber materials contribute to the improvement of their thermal insulation properties in the construction of the envelope. The number of studies that use natural and local materials as thermal insulation materials is growing and they highlight both the thermal performance and their ecological properties of these solutions [7].

The agro-industrial waste can be used as thermal insulation materials, providing recycling practices and eco-effective solutions. However, a lack of complete data on these raw materials' thermal conductivity and water absorption characteristics is significant; previous research has omitted crucial information about sample preparation, hindering accurate result comparisons [8]. In recent years, numerous studies have been conducted on using agricultural waste, such as coconut, coffee, corn, cotton and rice residues, for producing insulation materials [9]. Previous studies have developed composites using rice husks mixed with different materials and binders as glue to bind the husks [10–16]. For instance, a material based in rice husk as the primary component combined with natural binders of starch, alginate and casein demonstrated a higher density in the rice husk compounds between 210 and 290 kg /m^3 and a thermal conductivity between 0.073 and 0.098 W/mK, which are acceptable values for insulating materials [10]. Another study assessed the thermal, acoustic and environmental properties of recycled waste panels made from rice husk manufactured by gluing and pressing the raw material; these panels performed well at medium to high soundwave frequencies, exhibited high thermal resistance and had minimal environmental impact during the production phase [12]. Additionally, a study presented the manufacturing and evaluation of a cellulose- and rice husk-based insulation material. Experimental mechanical and thermal tests confirmed the feasibility of using rice husk but emphasized that further efforts are needed to optimize and develop these materials in terms of their properties, manufacturing and installation. Some limitations described in the study include fire treatments [16]. Another effective way requiring only low technology to process is the pulping method, which has been explored in previous works with other fibers like wheat straw, corn husk and eucalyptus bark fiber that, with the use of the chemical reagent NaOH, allows the lignin to be dissolved, which is a natural binder of the fiber itself [17,18] and relevant for use with the rice husk.

Peru is an agro-industrial country where more than 16 million metric tons of agricultural residues are generated annually, and rice husk is one of the primary residues. The annual production of rice is 3,151,400 metric tons, and Arequipa at the southern coast is one of the principal areas of rice cultivation [19]. The region of Arequipa, Peru, presents twelve of the thirty-eight climates of the country, with territories at altitudes higher than 4000 m above sea level. This region of the Andes presents minimum temperatures of −1 °C in summer and −11 °C in winter [20]; this, added to the conditions of the buildings in these areas generate inadequate thermal conditions [21,22]. However, less than 180 Km from these high Andean zones, cultivated areas on the coast generate agricultural waste that can be used to develop thermal insulation materials, such as paddy rice. Therefore, it is feasible to generate circularity schemes between the different zones, taking advantage of the needs and potentialities of the locality, as indicated in [2], by using materials with low cost and located close to the production centers. Moreover, their re-incorporation into manufacturing processes through the use of waste in a circular economy environment could become an opportunity for improvement and sustainable development.

Studies have shown that rice husks have good characteristics to be used as a thermal insulation material; nevertheless, the characteristics of rice husk-based materials ultimately depend on the production method, the rice husk percentage and the binder used. Therefore, using materials with low cost and located close to the production centers and their re-incorporation into manufacturing processes through the use of waste in a circular economy environment could become an opportunity for improvement and sustainable development. For example, the thermal conductivity of rice husk presents values from 0.046 to 0.057 W/mK [23], while other composites made with rice husk with the addition of binders show thermal conductivity values from 0.068 to 0.08 W/mK [9]; density, moisture content and application, among others, also influence the results in both cases [12].

The fire behavior of rice husk composites shown is diverse and depends on the binder and retardant treatment used. Previous work showed that composites with natural binders made with rice husk, corn pith and barley straw compared with polystyrene and polyurethane have very favorable fire properties [24].

In the case of sound absorption, a comparison revealed that the glued rice husk panel performs better at low frequencies up to 4000 Hz with peak of 0.87 at 2600 Hz, compared to the loose samples [12].

This research aims to develop a thermal insulation material by utilizing rice husk, an abundant agro-waste; this paper presents a detailed analysis of the thermal and acoustic performance as well as the fire behavior and the water absorption of rice husk panels produced through the pulping method. The results show that these panels can be developed as a competitive insulating material with other natural insulating materials with low environmental impact.

2. Materials and Methods

2.1. Materials

The rice husk was collected in the region of the Valley of Tambo in Arequipa, Peru, through the "Molino San Juan El Arenal". This product was obtained after the milling phase in the process to obtain rice; tests were made, and the findings presented the initial conditions in loose materials, a preliminary conductivity of 0.040–0.041 W/mK, densities of 130–170 kg/m^3 and moisture between 8.68 and 10.68 %. Table 1 summarizes the chemical composition in weight percentage (wt%) reported in the literature.

Table 1. Main chemical composition of rice husk.

Cellulose (%)	Hemicellulose (%)	Lignin (%)	Silica (%)	Ash (%)	Ref.
24.3	24.3	14.3	9–14	15.3	[24]
37.34	10.07	41.08	-	11.51	[25]
31.13	18.59	28.25	15–17	16.50	[26]

2.2. Sample Description

All samples were made in the laboratory through different tests. The samples included a rectangular prism measuring 16 × 4 × 4 cm for thermal and smoldering characterization, a square prism measuring 7 × 7 × 4 cm for the epiradiator test, and square panels of 30 × 30 × 2.5 cm and 30 × 30 × 4 cm for acoustic measurements. The prototypes were fabricated using distilled water, sodium hydroxide and rice husk via a pulping method; the fabrication process involved incorporating 900 g of the rice husk fiber in a 1 L solution made with pre-heated water at 80 °C and NaOH as a chemical reagent for the fiber treatment (Figure 1a). First, the mixture was boiled, then blended, washed, and casted in molds (Figure 1b). Finally, the processed fiber was dried. The times and proportions are described in Table 2.

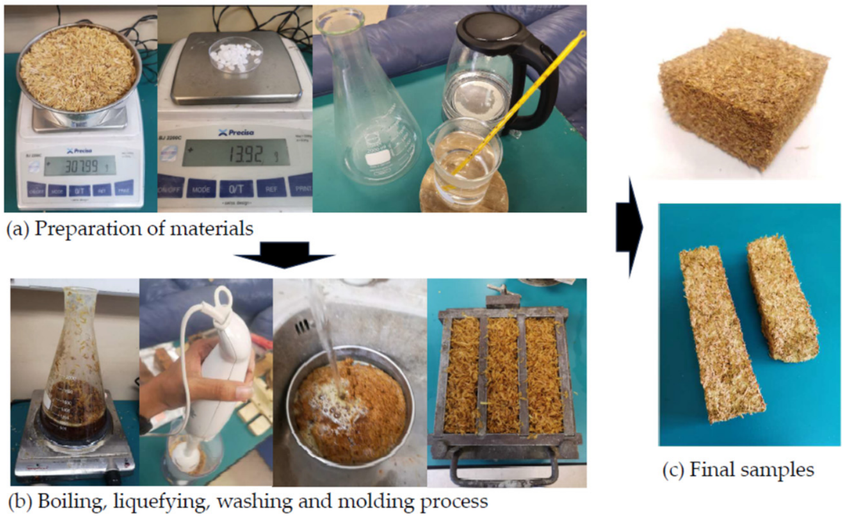


Figure 1. Steps in manufacturing the samples.

Table 2. Initial proposed parameters.

Factor	Proof 1	Proof 2	Proof 3	Unit
Boiling time	30	45	60	min
NaOH concentration	0.5	1	2	%
Blending time	5	10	20	s

2.3. Experimental Design

The Taguchi method uses orthogonal designs to combine engineering methods and statistics to assess the factor of entrance to systematically determine the interaction between them. The Taguchi method provides a systematic and efficient methodology for optimizing the design of system parameters and also uses the signal-to-noise ratio (SN) to analyze the effects of contributing factors on the responses [27]. Qualitek 4 software was used to process the data from "Automatic design and analysis of Taguchi experiments version 4.82.0" to obtain the optimum factor to develop the final prototypes of the rice husk samples.

The data shown in previous works were used to determine the parameters to be used in the pulp method in the first stage [17]. Three first experimental prototypes were made to determine the start point, and three parameters were determined to elaborate the first set of samples (Table 2): boiling time, the concentration of NaOH, and blending time. After processing the rice husk fiber, the results of thermal conductivity, density and consistency are shown in Table 3 on a scale from 1 to 3, from least to most consistent. Considering these preliminary results, working with the parameters of proof 1 did not guarantee good consistency, while proofs 2 and 3 were appropriate and were the reason for our choice of working with boiling times of more than 45 min, a concentration of at least 1% NaOH, and a blending time of over 10 s.

Table 3. Results of the first prototypes.

Proof	Thermal Conductivity W/mK	Density kg/m^3	Consistency
1	0.038	70.31	3
2	0.042	97.66	2
3	0.067	130.63	1

There are three control factors and three levels of each factor that will affect the results of rice husk panel manufacturing. The first factor is the boiling time (A), the second factor is NaOH concentration (B) and the third factor is the blending time (C). These levels were introduced in the program Qualitek 4 and shown in Table 4.

Table 4. Fabrication parameters.

Control Factor	Level			Unit
	Level 1	Level 2	Level 3	
A	45	60	75	min
B	1	1.5	2	%
C	10	15	20	sec

The three factors and levels of each factor were processed using Qualitek 4 software and produced the experimental design shown in Table 5. In the Taguchi method, the orthogonal array matrix is designed to provide the number of trials of the experimental design by selecting the L4 orthogonal array; in this study, the characteristics of the SN ratio used are "smaller is better" as the optimization process parameter.

Table 5. Design matrix of the Taguchi method of orthogonal array for experimental runs.

Trial Number	A	B	C
1	1	1	1
2	1	2	2
3	2	1	2
4	2	2	1

In order to optimize the prototype, an analysis of the SN relation was conducted to obtain the lowest values of thermal conductivity. Utilizing Qualitek 4 software, an ANOVA analysis was performed, revealing that blending time has the most significant influence on thermal conductivity at 64.44%, followed by boiling time at 34.50%. In addition, the increase in NaOH concentration can reduce the insulating capacity, and this indicates that selecting a medium level of NaOH concentration, a high level of blend, and a medium level of boiling time targets the lowest thermal conductivity. The factors that produce optimal prototypes in the experimental design are shown in Table 6. This combination was utilized to produce the samples for the tests in the current study.

Table 6. Factors to produce optimal prototypes.

Factor	Value	Unit
Boiling time	60	min
Additive concentration	1	%
Blending time	15	sec

2.4. Scanning Electron Microscopy (SEM)

The morphological visualization of the rice husk and prototypes was performed through scanning electron microscopy (SEM) with a VPSEM SU 3500 microscope produced by Hitachi. Tokyo, Japan. The following conditions were required: magnification 40-100-200-500× (superficial cut) and 30-100-200-500× (cross-section), detector BSE, 10KeV, WD12 mm, 30 Pa, according to laboratory equipment specifications [28].

2.5. Thermal Tests

2.5.1. Thermal Stability

The thermogravimetric (TGA) analysis TGA/DSC STA 6000, Perkin Elmer, Shelton, EEUU, was used to analyze the thermal stability of the rice husk and the processed samples, the purge gas was set at 40 mL/min, and the gas used was nitrogen (N2) at 40 mL/min.

The mass of the sample was 20.233 mg, and the temperature program used was as follows: The sample was heated from 25 to 120 °C at a rate of 50 °C/min; then, it was held for 3 min at 120 °C. Afterwards, it was heated from 120 to 950 °C at a 100 °C/min rate, and then cooled from 950 to 450 at 100 °C/min. The change from gas to oxygen was carried out at a 40 mL/min flow under heating from 450 to 800 °C to 100 °C/min, and finally held for 3 min at 800 °C [29].

2.5.2. Thermal Conductivity Density and Moisture

The prototypes´ thermal conductivity was determined using the transient line heat source method with the KD2Pro device manufactured by Decagon Devices Inc., Pullman, EEUU (Figure 2); other studies used it with different insulation materials [17,18,30,31]. This equipment measures at intervals of 1 s during a heating and cooling cycle of 90 s; KD2 complies with the IEEE 442-1981 [30] specifications and ASTM D5334-08 standards [32]. The accuracy of these tests was ±0.001 W/(mk). A 10 min gap between analyses was determined to ensure the stabilization of the sensor. The density was determined by the geometric calculation that relates the mass and the volume of the samples. The moisture data were measured using moisture analyzer model BMA H50—"Moisture analyzer" Boeco, Hamburg, Germany (Figure 3), which operates with halogen light in a working temperature range of 10–40 °C and delivers results with an accuracy of 0.001%. The analyzer in the process of measurement is shown in Figure 3.

Figure 2. Thermal conductivity measurement equipment.

Figure 3. Process of measurement of moisture.

2.6. Water Absorption

For this test, the samples were immersed in distilled water at intervals of 2, 12, and 24 h [33] to measure the weight of the sample after immersion; the excess water in the surface of the sample was removed with tissue paper, and the percentage of water absorption was calculated using Equation (1) which was used in previous work [15]:

$$Water\ absorption\ (\%) = \frac{Wf - Wi}{Wf} \quad (1)$$

where *Wf* is the weight of the sample after immersion in water and *Wi* is the sample weight (dried) before immersion in the water.

2.7. Fire Behavior

To analyze the fire behavior of the rice panels, a fire reaction test, epiradiator test and a flameless test to asses smoldering combustion were performed; in each case, the samples were made with and without flame retard treatment and compared with other commercial natural insulation materials.

2.7.1. Epiradiator Test

Rice husk samples with and without flame retardant were tested; a commercial wood fiber insulation containing boron salts was also tested to compare. In order to prepare flame-retarded rice husk samples, the rice husk fiber was added to water-based solutions containing the flame retardants and kept for 24 h to continue with the regular process described in Section 2.2 of molding and drying. The samples of rice husk without flame retardant treatment (RH-U) and with flame retardant treatments of 5% of H_3BO_3 and 5% of borax (RH + 10% H_3BO_3 + borax), 10% of disodium octaborate tetrahydrate with the commercial name Solubor (RH + 10% Solubor), and wood fiber (WF) were subjected to a fire reaction test using an epiradiator (Figure 4) according to the standard UNE 23.725-90 [34]. Specimens of 70 × 70 × 40 mm were put on a metallic grid 3 cm below a 500 W heating source, resulting in a heat flux of 3 W/cm^2. The radiator was removed after the ignition of the sample and replaced after the extinction; this process was repeated for 5 min during the test [34]. The time of the first ignition, the flame persistence time, the number of ignitions and the sample weight loss were determined.

Figure 4. Epiradiator test.

2.7.2. Smoldering Combustion Analysis Test

Smoldering is a phenomenon of combustion without flame, which is especially crucial in combustible porous materials. To determine smoldering velocity, an elongated specimen of 40 × 40 × 160 mm was held on top of a hot plate and the evolution of the temperature was recorded with six type-k thermocouples. The first one was in direct contact with the hot plate, the next one was placed at 0.5 cm, and the others every 3 cm along the vertical centerline of the sample (Figure 5). In the experiments, the hot plate was heated for 1 h until it reached a predeterminate temperature of 360 °C, then allowed to cool to room temperature for 1 h. The evolution was also visualized during the experiments with an infrared camera, and images were taken every 5 min [35,36]. Smoldering velocity was evaluated based on the temperature recorded by the thermocouples by determining the times at which each thermocouple positions reach a temperature of 270 °C.

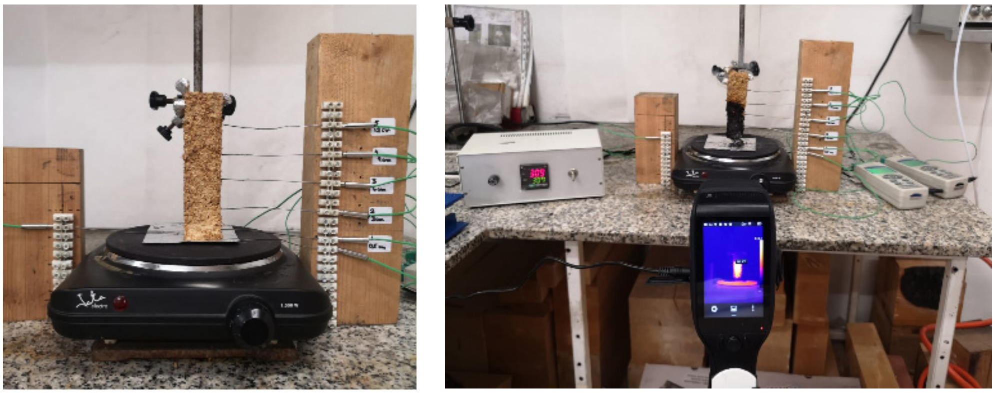


Figure 5. Smoldering setup.

2.8. Acoustic Test

Sound Absorption Measurement

The acoustic characterization of the materials was performed by means of an in situ sound absorption equipment from Microflown Technologies. The method uses a high-precision P-U probe that allows for the simultaneous determination of acoustic pressure and particle velocity. The test was made in the laboratory on two square samples of 30 × 30 with different thicknesses of 4 cm and 2.5 cm; a tripod was used to fix and stabilize the device during the test, and the measurements were taken at a distance of 5 mm above the surface of the sample [37].

Figure 6 shows the experimental setup. It consists of a spherical loudspeaker of 11 cm diameter and a P-U probe. The distance between the loudspeaker and the P-U probe is kept constant and equal to 27 cm. The loudspeaker generates a continuous white noise and the P-U probe measures the sound pressure and the velocity of the air particles on the surface of the material. The relationship between P and U allows us to calculate the reflection coefficient and thus the absorption coefficient. A software controls the measurement and allows for the determination of acoustic parameters in the frequency range between 125 Hz and 4000 Hz [37,38]. This section presents methods for finding the optimal variables to make an insulation material with rice husk via the pulping method and for measuring their physical properties as thermal, surface analysis, fire behavior, and acoustic properties.

Figure 6. Point of measurement in the acoustic samples and in situ setup of the probe.

3. Results and Discussion

3.1. Scanning Electron Microscopy (SEM) Analysis

Two stages were made for the microscopic analysis of the rice husk, the first one in the natural state shown in Figure 7a–c and the second one for the processed prototype shown in Figure 7d–f.

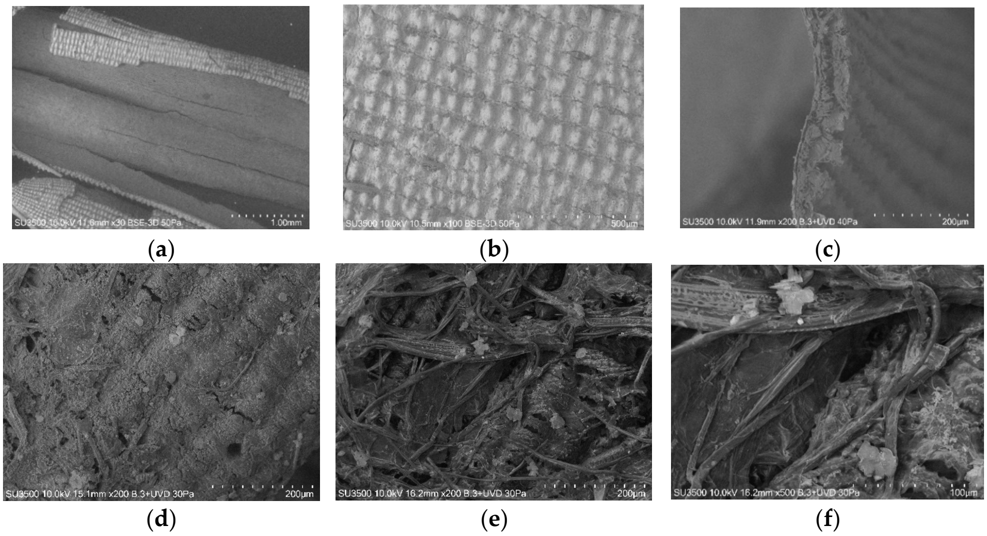


Figure 7. SEM analysis: (**a**) internal longitudinal; (**b**) external longitudinal; (**c**) cross-section of natural rice husk; (**d**) internal longitudinal; (**e**) external longitudinal; (**f**) cross-section of processed rice husk.

Figure 7a shows the internal and Figure 7b the external longitudinal surface of the rice husk, showing the entire surface of well-defined pores that can help achieve optimal levels of thermal insulation. After carrying out the pulping method, this structure was maintained as shown in Figure 7d; this is considered very important for insulating materials because this helps to maintain a good homogeneity of the material. Furthermore, the elongated fibers that give it its thermal capacity can be seen. A small white cluster is observed, which comprises particles of NaOH used in the pulp method; these particles are homogeneously mixed throughout the material [17,28]. The presence of sodium (Na) in the elemental analysis performed by EDS (energy dispersive spectroscopy) and shown in Figure 8 confirms the homogeneous distribution on the surface of the structure of the processed prototype. The presence of silicon can also be observed, probably forming silica, which will positively contribute to the fire performance [14,39].

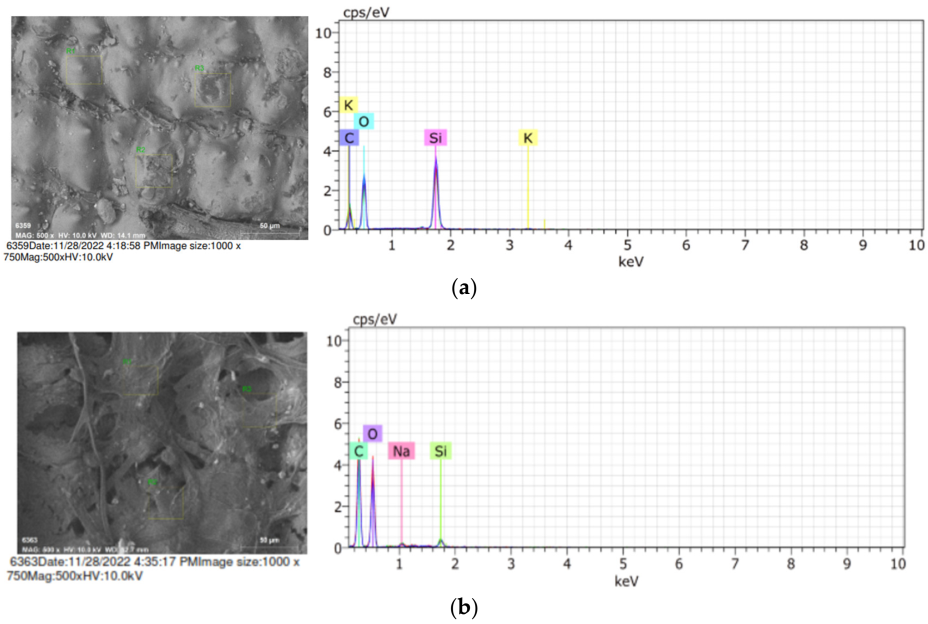


Figure 8. Energy dispersive X-ray spectroscopy (EDS): (**a**) natural rice husk; (**b**) processed rice husk.

3.2. Thermal Test

3.2.1. Thermal Stability

The proximal analysis carried out on rice husk in its natural state is detailed in Figure 9. According to the TGA, the fiber begins to lose weight at 125.27 °C, corresponding to 8.25% of weight loss mainly related to moisture. Subsequently, from 125.27 °C, there is a more significant mass loss of 54.45%, which is associated with the volatile compound's hemicellulose and cellulose. Once the environmental change to oxygen takes place, there is a fixed carbon loss of 17.36% corresponding to lignin. Finally, at 800°C, the percentage of ashes was 19.93%.

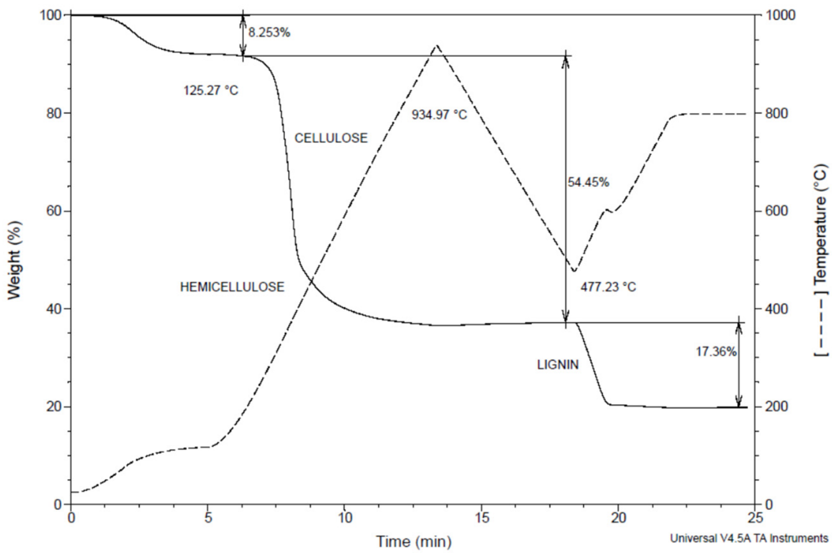


Figure 9. Thermal stability of rice husk (TGA).

The rice husk fiber presents stability until 125 °C, indicating that the temperature for processing should be lower than this value to avoid thermal degradation; similar results are shown in the studies [17,40]. These results agree with the chemical analysis reported in the literature and shown above in Table 1. As can be seen from Figure 7, the rice husk stayed thermally stable up to 125 °C above these temperatures' thermal degradation start, which is similar to those reported in other studies of rice husk TGA [11,12] in the average of other natural fibers like wheat straw, corn husk and pisum sativum [17,29], and is higher than other natural fiber composites mixed with some binders [25,40].

3.2.2. Thermal Conductivity

The thermal conductivity of each sample made under the matrix given by the Taguchi method was measured four times from M1 to M4 to determine its average, and a general average of 0.037 W/mK ± 0.001 was observed, Table 7. Values of the optimal prototype are shown in Table 8. The thermal conductivity obtained for the rice husk panel was 0.037 W/mK; this value is lower than other natural thermal insulation made by the pulp method bordering 0.046 and 0.047 W/mK and other rice husk panels made with a different class of binders from 0.068 to 0.080 W/mK as shown in Table 8. In general, the thermal conductivity of the prototypes is competitive with other natural thermal insulation; the material could be used to insulate buildings and reaffirm the opportunity to develop new materials through the use of agro-waste.

Table 7. Thermal conductivity of Taguchi matrix W/mK.

Thermal Conductivity					AVG	SD
	M1	**M2**	**M3**	**M4**		
Sample 1	0.033	0.032	0.032	0.035	0.033	0.0014
Sample 2	0.038	0.041	0.042	0.045	0.042	0.0029
Sample 3	0.035	0.036	0.036	0.036	0.036	0.0005
Sample 4	0.036	0.038	0.035	0.038	0.037	0.0015
			Thermal conductivity W/mK		0.037	0.0016

Table 8. Main thermal conductivity, density and moisture of natural thermal insulation material.

Biomass	**Processed Type**	**Thermal Conductivity W/mK**	**Density kg/m³**	**Moisture %**	**Ref**
RH Optimal Prototype [1]	Pulp method	0.037 ± 0.001	97.32 ± 6.42	8.78 ± 0.17	
Rice Husk	Without	0.049	149	-	[23]
Wheat straw	Pulp method	0.046	104.84	7.54	[17]
Corn husk	Pulp method	0.047	118.79	7.65	[17]
Rice husk ecovio	Bio-polymer composite	0.08	378	-	[15]
Rice husk	Binder liquid gas	0.068	230	-	[41]
Rice husk	Gluting and pressing	0.070	170		[12]

[1] Optimal prototype of the present study.

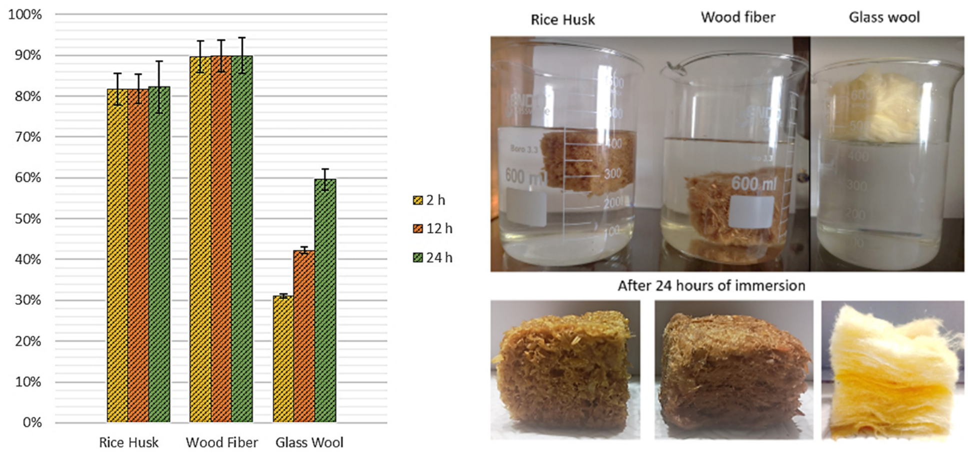
3.2.3. Density and Moisture

The density of the optimal prototype was 97.32 kg/m^3; the values of the rice husk panel are in the range with other natural thermal insulation made through the pulping method, as shown in Table 8, but are higher than other insulating materials like rock wool at 27 kg/m^3 or polystyrene at 10 kg/m^3. Like other organic materials, the rice husk panels' thermal conductivity increases if the density increases as well.

Moreover, the moisture content of the samples has an average of 8.78 ± 0.17%; this value is similar to other natural fiber materials as reported by their authors [8,15,17,18], which is a low value and is desirable because a high content of moisture could affect the thermal properties of an insulation material [7], increase condensation, and decrease biological resistance. Furthermore, when the level of moisture is generally low, the biological resistance is better for buildings materials [20].

3.3. Water Absorption

The water absorption of the rice fiber panel sample was compared with wood fiber and rock wool samples; Figure 10a represents the percentage of water absorption in the samples. When comparing organic samples, it was observed that after 24 h of immersion in water, all rice husk samples showed an absorption rate of around 80%, the rate absorption for wood fiber samples was found to be around 90%. Although the rice husk samples exhibit a similar behavior to the wood fiber ones, they have a lower water absorption percentage. This can be attributed to the presence of a silicon cellulose membrane on the surface of the rice husk, which makes it hydrophobic and reduces its absorption capacity [15]. Moreover, saturation is nearly achieved after 2 h of immersion due to the high absorption kinetics. Additionally, the sample showed no appearance of cracks even after 24 h of immersion, and there were no losses in its size. The rice husk samples were observed to be cohesive after the test, as shown in Figure 10b.



(**a**) (**b**)

Figure 10. (**a**) Percentage of water absorption in samples of the rice husk, wood fiber and glass wool; (**b**) the samples after 24 h of immersion.

Compared to traditional insulation materials such as glass wool, natural fibers exhibit higher absorption. However, to avoid issues such as biological corrosion and loss in thermal insulating properties, it is crucial to protect the material with a final construction solution. Natural materials are highly sensitive to moisture and are mostly vapor-permeable, which can cause moisture accumulation in an internal porous system. Therefore, it is mandatory to use an adequate construction solution that guarantees the prevention of these problems and protects the material from sources of moisture; these findings are supported by the existing literature [7].

3.4. Fire Behavior

3.4.1. Epiradiator Test

Table 9 describes the behavior of the samples; it can be seen that the first ignition time of RH-U samples is similar to those reported for composite rice husk material made with natural binders [24]. The samples with RH + H_3BO_3 + borax treatment have a very significant effect in delaying the first ignition and reducing the number of ignitions, presenting a 65.71% improvement ahead of the RH-U. In addition, the results summarized in Table 9 highlight the high performance of the samples of RH + 10% Solubor, which, in this short-term exposure test, did not present ignition, only formed a carbonized layer that protects the sample from burning, and gives it good fire behavior, which can be observed in Figure 11, where the samples after the test are shown. Wood fiber (WF) insulation is wholly consumed, while non-retardant rice (RH-U) is not due to the silica content of the rice husk. Samples with retardant are only superficially affected thanks to the protection provided by borate-based flame retardants, which tend to form a protective glassy layer that hinders the release of combustible gases and the access of oxygen. Compared with the WF, RH with and without treatment has better behavior in the first ignition time and the average combustion extent.

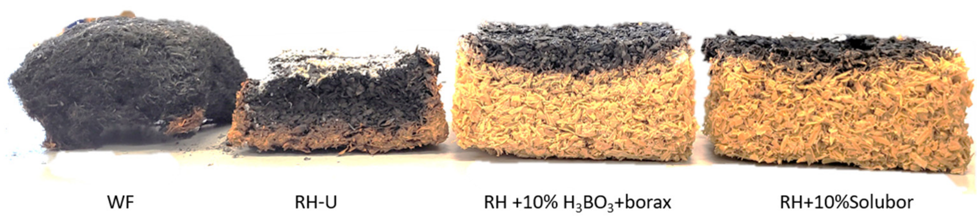


Figure 11. Samples after epiradiator test.

Table 9. Epiradiator ignition and extinguishability test results.

Treatments	First Ignition Time (s)	N° of Ignitions	Average Combustion Extent (s)	Initial Mass (g)	Final Mass	Loss	Percentage %	Smoldering
WF	3	30	9	17.87	3.64	14.23	79.63	Yes
RH-U	7	29	4	36.22	5.96	30.26	83.55	Yes
RH + 10% H_3BO_3 + borax	36	12	4	39.59	29.1	10.49	26.50	Yes
RH + 10% Solubor	0	0	0	33.59	25.76	7.83	23.31	No

3.4.2. Smoldering Combustion Analysis Test

For this smoldering test, samples of the size of 4 × 4 × 16 cm of untreated (RH-U), with retarded treatment (RH +10% H_3BO_3 + borax and RH + 10% Solubor), and wood fiber (WF) were evaluated. During the experiments, the evolution of smoldering was visualized with an infrared camera. Figure 12 shows the results; the images are presented in a sequence of seven pictures taken every 10 min from 50 min to 110 min; the green color corresponds to temperatures around 270–350 °C. The evident smoldering begins at 65 min, while with wood fiber, starting at 55 min.

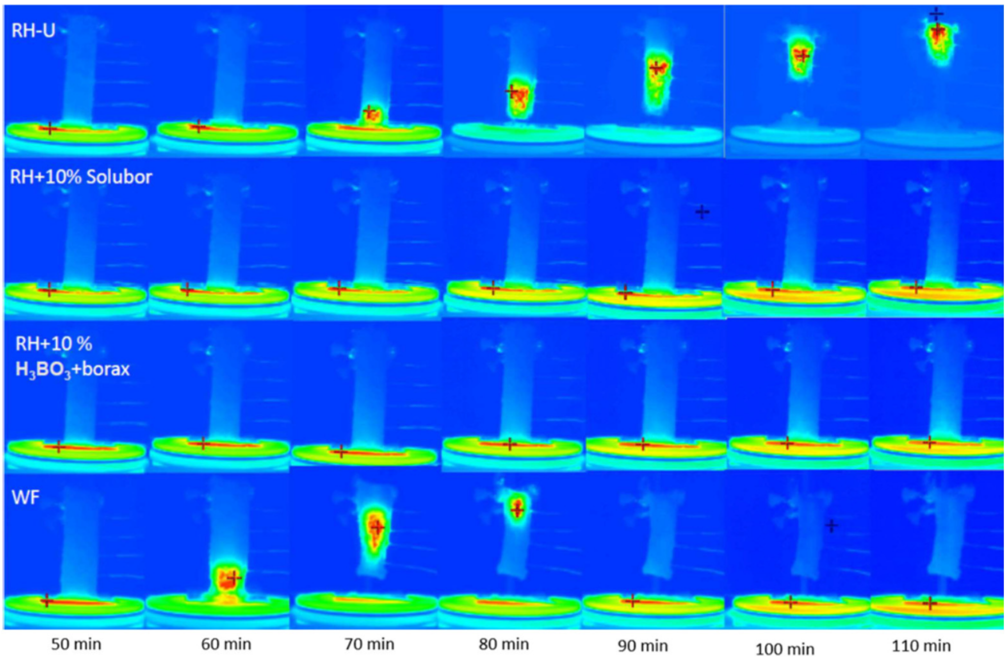


Figure 12. Smoldering process thermography.

The samples treated with RH + H_3BO_3 + borax and RH + 10% Solubor did not experience smoldering; however, the samples RH + 10% Solubor presented a better behavior, reaching the first thermocouple temperatures of 177 °C as opposed to the sample treated with H_3BO_3 + borax that reached temperatures of 237 °C, a difference of 60 °C.

Figure 13 shows the temperatures (°C) recorded by the thermocouple (T) on samples tested to a pre-set temperature of 360 °C; the dashed lines correspond to the temperatures measured at the hot plate surface. From these data, smoldering velocity can be evaluated by determining the times (min) at which each thermocouple position reaches a specific temperature here, and it is chosen as 270 °C; the RH-U shows better behavior in the smoldering test than the WF both in the temperature and velocity of smoldering, reaching maximum temperatures of 629 °C and for the wood fiber at 711 °C. The velocity of smoldering is faster in the WF with 6.30 mm/min; meanwhile, the RH-U is 3.40 mm/min, as shown in Figure 14. A previous work involving corn pith panels with the use of boric acid as a fire retardant presented speeds between 6.6 and 10 mm/min [36], while the rice husk has a slower smoldering speed.

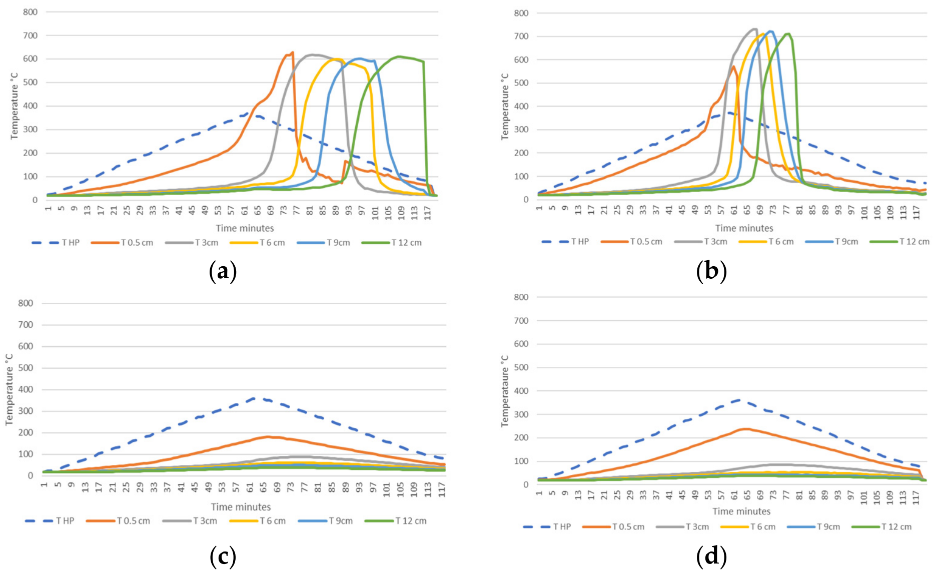


Figure 13. Temperature evolution for thermocouples located every 3 cm along. Pre-set temperature of the hot plate: 360 °C. (**a**) RH untreated; (**b**) wood fiber; (**c**) RH + 10% Solubor; (**d**) RH + 10% H_3BO_3 + Borax.

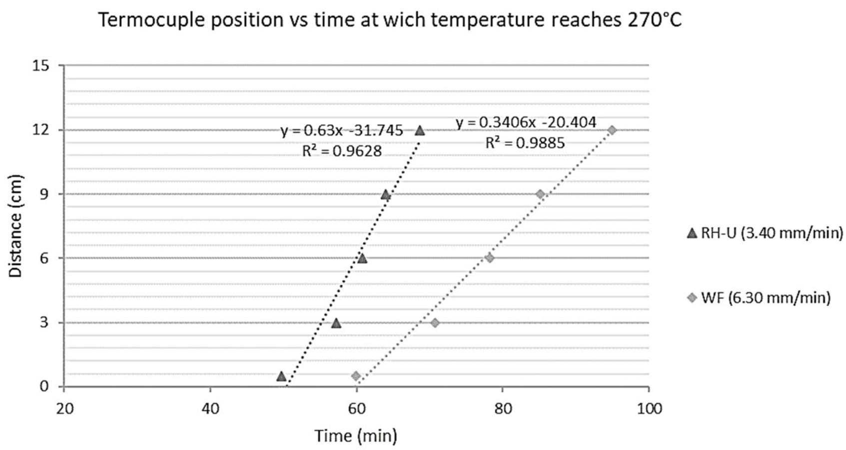
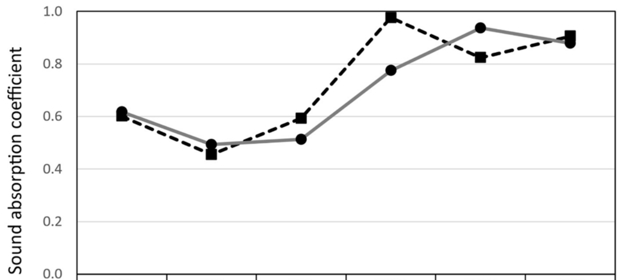


Figure 14. Smoldering propagation velocities are calculated as the slope of the obtained linear regression.

3.5. Sound Absorption Measurement

Sound absorption measurements were taken on 30 × 30 cm square rice husk samples using in situ equipment. Two thicknesses were evaluated 4 cm (S1) and 2.5 cm (S2). Eight measurements were taken, four for each side. The first measurement was taken at the center of the sample, and the other three were taken at points 8 cm away from the center. The distance between the P-U probe and the sample surface was 5 mm; as suggested in [37], a tripod was used to maintin the setup during the probe.

Figure 15 shows the results obtained for octave bands between 125 Hz and 8 kHz. In both cases, the sound absorption is high, with coefficients very close to 1 in some bands. Sample S1 presents a value of 0.98 in the 1000 Hz octave band and sample S2 a value of 0.94 in the 2000 Hz octave band. A similar behavior has been pointed out by other authors who analyzed natural thermal insulators, such as kenaf, coconut fibers or cork [42,43].



	125	250	500	1000	2000	4000
S1 (4 cm)	0.60	0.45	0.59	0.98	0.82	0.91
SD	0.01	0.02	0.01	0.01	0.01	0.01
S2 (2.5 cm)	0.62	0.49	0.51	0.77	0.94	0.88
SD	0.02	0.01	0.01	0.07	0.03	0.02

Frequency (Hz)

Figure 15. Comparison between the sound absorption coefficients obtained for the two samples. In each case, the average of 8 measurements and their standard deviation, evaluated in octave bands, is shown.

Although the results for both samples are similar, some dependence on thickness is observed. On the one hand, a greater thickness leads, as expected, to a higher overall absorption. The noise reduction coefficient (NRC), calculated by taking the mean values of the sound absorption coefficient at frequencies of 250 Hz, 500 Hz, 1000 Hz and 2000 Hz, gives values of 0.75 for the 4 cm sample (S1) and 0.72 for the 5.5 cm sample (S2). On the other hand, it is observed that as the thickness is reduced, the absorption peak shifts to the right (higher frequencies). This behavior is qualitatively in agreement with the work by C. Buratti et al. [12] who analyzed loose rice husks by varying the thicknesses using an impedance tube.

4. Conclusions

An alternative to ecologically friendly materials is natural insulation materials. In this research, a rice husk panel has been developed and characterized through the pulping method. The evaluation of thermal behavior, water absorption, fire behavior, and sound absorption performance was conducted.

The optimal prototype resulted in a thermal conductivity of 0.037 ± 0.001 W/mK with a density of 97 kg/m^3.The rice husk fiber is an excellent alternative to work through the pulping method because voids are generated between the fibers, which is better for improving their insulation capacity. The thermal conductivity results show that it is lower than other natural fiber insulation materials made with the same production method, and it is very competitive with other natural fiber composites with binders. The proposal is an attractive thermal insulation solution for the building industry as it is competitive with the commercial ones.

The rice husk panel showed good fire behavior. Regarding the reaction fire test, the samples of untreated RH presented a good performance compared with other lignocellulose materials for its percentage content of silica. In the case of the smoldering velocity, almost a 50% reduction in velocity compared with the wood fiber was seen, but to improve the fire behavior of the material, flame retardant treatments are necessary. Solubor (sodic borate 17%), already used in ecological agriculture, was found to be the best treatment option in this research. However, further research is required to identify low-impact and/or natural flame retardants.

The acoustic behavior, for two panel thicknesses, has been evaluated by determining the acoustic absorption coefficient in octave frequency bands between 125 Hz and 4 kHz. The NRC values obtained have been, in both cases, greater than 0.7, which means an excellent acoustic absorption capacity.

Implementing and applying the rice husk panels within the construction system requires special care, just like other insulating materials made with natural fiber. The panels must have an appropriate format and be protected in the construction solution, considering their density and water absorption percentage. Proper precautions must be taken to ensure their effectiveness in the construction solution. Further investigations should include the use of simulation programs to evaluate the application of this type of material in buildings.

The results show that the rice husk panels by the pulping method are an interesting solution in thermal, acoustic and fire behaviors, showing good technical performances; furthermore, rice husk is an important agro-waste in Peru and have the potential to produce building insulation materials.

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