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Research Article

Reuse of banana fiber and peanut shells for the design of new prefabricated products for buildings

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Abstract: This work presents a sustainable panel elaboration for housing interiors through banana fiber and peanut shells gathered from crop residues, consolidated with a polyester resin binder. A material characterization process was defined by forming three prototypes with different dosages. The prototypes performed physical and mechanical tests following recommendations from previous research and the standards. The results obtained were favorable regarding thermal transmittance percentages, achieving an average resistance comparable to non-structural medium density particleboard (MDP). Performance comparisons were also established, which depict the potential of these prototypes to contribute to the building industry, including the development of thermally comfortable environments.

Keywords: polymer; fibers; crop waste treatment; insulating panel.

1. Introduction

The banana (Musa x paradisiaca) is one of the agricultural commodities with the highest production. This product trades worldwide, with rising productivity from 69 million tons in 2002 to 116 million tons in 2019, whose main producers are Brazil, the Philippines, India, China, and Africa. It is a fruit sought after for its flavor and nutritional value, creating new markets in the European Union and the Russian Federation. The cultivation areas expand with the necessary inputs for this activity, such as fertilizers and pesticides (FAO, 2000) to meet the domestic and international consumptions. This agricultural process also results in a large amount of crop waste that affects soils because of the decomposition of organic matter with a high content of nutrients such as nitrogen, phosphorus, and potassium, which are present in fertilizers (OECD, 2008). It also encourages eutrophication through leachates that are carried by surface and subway runoff, contaminating bodies of water such as lakes, lagoons, rivers, and reservoirs, among others (FAO, 2002).

The peanut (Arachis hypogaea L.) is a leguminous plant with a semi-hard shell, rich in oil and proteins, original from Brazil. Its production is concentrated in developing countries, with 95% of world production. Asia accounts for 70%, where China and India produce two-thirds (Nautiyal P.C., 2002), leading a world production of peanuts about 46,058 million tons. China is the world principal producer with 38%, followed by India 14%, Nigeria 8%, and the United States 5% (USDA, 2019). Studies estimate that there are 200 to 300 grams of Shell per kg of peanuts. It is worth mentioning that the worldwide shell waste production is nearly 10.7 to 14 million tons between 2017 and 2018 (Ge et al., 2020). These harvests increase as the industry diversifies the product presentation in several foodstuffs such as confectionery. It also contributes to the awareness of good nutrition provided by the seed and its oil with a high protein content and energy value (Nautiyal P.C., 2002). The elimination of these residues is through open burning, causing environmental deterioration, which affects the soil where they carry out the incineration, the air by the emanation of CO2, NOX, leading to respiratory problems in people living in surrounding areas by the inhalation of ashes (FAO, 2002).

Agriculture is an example of anthropization, it occupies large wildland to produce crops that meet specific needs, regardless of the endemic species presence. This activity, combined with other livestock activities, implies an impact on the environment combined with livestock occupation, which contaminates water bodies due to fertilizers and pesticides with high chemical content, contributing to greenhouse gases such as methane and nitrous oxide (FAO, 2002). The open burning of agricultural waste is a custom still practiced worldwide. This kind of waste elimination is a quick and cheap way to eliminate, clean, and clear cultivated areas. Researchers estimate that the burning of biomass from agricultural residues, including husks, wood, leaves, and trees, contribute to 40% of carbon dioxide (CO2), 32% of carbon monoxide (CO), 20% of suspended particulate matter (PM), and 50% of polycyclic aromatic hydrocarbons (PAHs) emitted around the world (Comisión para la Cooperación Ambiental, Montreal, 2014). It is also a source of dioxin, conditioned by the combustion type, the presence of chlorine, and the content of pesticides (Comisión para la Cooperación Ambiental, Montreal, 2014). Considering this, in the next 30 years, the environmental problems caused by agriculture will continue to grow (FAO, 2002).

Thus, world leaders have taken different actions through consensus achieved in several summits established by the United Nations (UN), based on the environmental deterioration the planet has suffered. The first one took place in Stockholm in 1972, named Human Environment. It was followed by the Environment and Sustainable Development, celebrated in Rio de Janeiro in 1992. Later, Johannesburg was the headquarter by 2002, with the World Summit on Sustainable Development. Then, the Conference on Sustainable Development took place in Rio de Janeiro in 2012 (Rio+20) and finally, in September 2015, the General Assembly of the United Nations in New York embraced the 2030 Agenda with 17 Sustainable Development Goals (ONU, 2021).

Sustainable development encourages the search for economic, social, and environmental balance, satisfying present needs without compromising the resources of future generations (ONU, 2020). One of the ways to contribute to the sustainable development of nations, especially those that rely heavily on the primary economy, is through the use of agricultural wastes by a recycling process, to convert them into a source of raw material for the production of construction materials that satisfy quality parameters (Pinto et al., 2012). In this regard, the usage of lignocellulosic waste in eco-friendly composites of several kinds is a valid alternative (Belhadj et al., 2020; Jami et al., 2019). In cases where the characterization and dosage are optimal, even an improvement of some properties can be achieved when comparing with the reference materials (Thongtha et al., 2014).

Cleaner production of aggregates from industrial waste is an alternative to natural stone aggregates (Merino et al., 2017). Anyway, the lower crushing strength of lignocellulosic aggregates resulted in subsequent changes in the mechanical resistance, increasing the replacement levels and durability properties of composites. These products incorporate a thermal insulation capacity as positive factor (Rojas et al., 2019) due to the density reduction of the composites (Chinnu et al., 2021).

The world population is growing progressively from 6.8 billion inhabitants in 2009 to 7.7 billion in 2019, with a projection of 9.7 billion by 2050 (World Population Clock: 7.9 Billion People (2022) - Worldometer, n.d.). The population density requires adequate space habitats to develop their activities, directly stimulating the construction industry (Maraveas, 2020). Currently, it is not a sustainable activity because it requires a vast number of conventional materials, such as cement, sand, metal, steel. These materials produce high pollution levels in their manufacturing processes (Shafigh et al., 2014), consuming large amounts of thermal and electrical energy, which increases expenditures. In addition, the manufacture of cementitious materials increases the carbon footprint and deteriorates the environment (Guna et al., 2020).

To contribute to the set of sustainable cities and communities in response to the global need to reduce pollution and its effects, researchers approach the use of agricultural wastes, especially lignocellulosic wastes due to their properties, for the manufacture or improvement of construction materials, as shown in V. Guna et al. (Guna et al., 2020). These authors proposed the usage of rice husk and peanut shells, without pretreatment, to prepare hybrid polypropylene biocomposites for environmentally friendly building materials. The materials possessed good tensile and flexural strength, a low thermal conductivity and a good maximum sound absorption coefficient.

Several types of research undergo on polymer composites reinforced with plantain lignocellulose fiber, whose extraction is from the plant pseudostem. M Ramesh et al. (Ramesh et al., 2014) present a study development of a banana fiber reinforced resin composite with volumes of 40%, 50%, and 60% of fiber. The composites with the latter two percentages of fiber produced higher tensile strength at 112.6 MPa and higher flexural strength at 72.2 MPa. On the other hand, N. Amir et al.(Amir et al., 2017) and Nensok et al. (Nensok et al., 2021) present in their research that composites with banana fiber experience higher mechanical strength compared to unreinforced polymers. Besides, they made three sampling processes: the first in PP (polypropylene) with banana yarn, the second in PP with raw banana fiber, and the third in PP and banana mat. The first sample provided higher tensile strength with 77.74 MPa, mainly due to the fiber arrangement going to the tensile load axis. The chemical treatment with NaOH of the banana fiber improves its mechanical response and permeability (Gairola et al., 2021; Laxshaman Rao et al., 2021).

H. Binici and O. Aksogan (Binici & Aksogan, 2017) present an insulating material development against radioactive and thermal emissions. They used fly ash, pumice, perlite, barite, cement, and gypsum as components, together with onion skin fiber and peanut shell, which resulted in values lower than 0.1 W/m·K in their experimentations. These indicators are considered insulating material according to international standards. The radioactive permeability of the samples is better at the 6.0 keV energy level (99.5%). The sampling process met both the compressive and bending stress tests. In addition, these components can apply as thermal insulation material in buildings and as radiation absorbers in hospital buildings and X-ray laboratories, among others. The present research aims to use the banana pseudostem and peanut shell fiber, with fibers gathered from the canton of Chone, province of Manabí, Ecuador, which has a vast extension of crops of these species. It was attained by selecting the fibers from the crop residuals to make an insulating panel by using polyester resin as a conglomerate. The approach was on the natural reinforcement of the agricultural residues in the polymeric matrix. Their mechanical tensile strength was analyzed and the thermal transmission capacity of each sample was evaluated.

This work aims to reuse banana pseudostem fiber and peanut shells obtained from the harvesting wastes for its usage with minimum treatment as a cost-effective solution to produce an architectural panel with insulating properties. The treated wastes were mixed with polyester resin as a binder for the consolidation attainment of the prototypes. It is descriptive research developed through the formulation of a hypothesis. Then, a subsequent verification was carried out through experimentation and characterization of the samples, together with the analysis of the results (Hernández & Mendoza, 2018).

2. Method

This research is in a preliminary phase, in which the fibers did not undergo chemical manipulation for property improvements. Therefore, the natural behavior of the two fibers merged in a polymeric matrix of polyester resin was analyzed. For testing, three prototypes were made with a base dimension of 30x30 cm with thicknesses of 5, 2.5, and 1.8 cm (see Fig. 1). Besides, we dosed the components for then mixed and co-located them in a mold, remaining in the matrix for five days for setting, with an ambient temperature of 28°C, supporting a weight of 50 kg to improve its compactness. After removing the mold, the samples remained at rest for five additional days due to the resin exothermic properties. Moreover, physical tests were performed to determine the EN 323 density (UNE EN 323:1994 Wood-Based Panels - Determination of Density - European Standards, n.d.), the EN 317 water absorption capacity (UNE EN 317:1994 Particleboards and Fibreboards - Determination of Swelling in Thickness after Immersion in Water - European Standards, n.d.), and the ISO 8302 thermal transmittance rate (ISO - ISO 8302:1991 - Thermal Insulation - Determination of Steady-State Thermal Resistance and Related Properties - Guarded Hot Plate Apparatus, n.d.). Mechanical tests were also conducted to define the modulus of rupture in static bending (MOR) EN310 (UNE EN 310:1994 Wood-Based Panels - Determination of Modulus of Elasticity in Bending and of Bending

Strength - European Standards, n.d.)and the compressive strength ASTM D1037 (ASTM D1037-12 - Standard Test Methods for Evaluating Properties of Wood-Base Fiber and Particle Panel Materials, n.d.).

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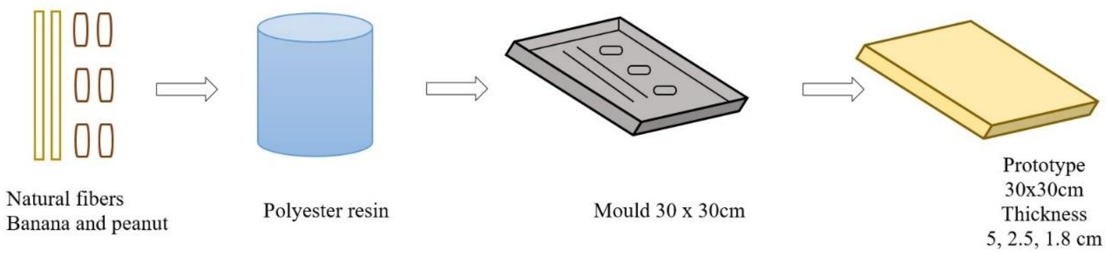

Figure 1. Prototyping process.

The prototypes were subject to an air-conditioned room with a temperature of 20°C and relative humidity of 65% until reaching the equilibrium moisture content before cutting the samples for testing. Samples were used to determine density and thermal transmittance, for measuring the absorption, compressive strength tests and the modulus of rupture. The test results were evaluated based on the relationship between the proportion of fibers, the thickness of the samples (5, 2.5, 1.8 cm), and their influence on the density. The latter has a directly proportional relationship to the strength characteristics of the prototypes (Dönmez Çavdar et al., 2013).

To determine the density, based on the EN 323 standard (UNE EN 323:1994 Wood-Based Panels - Determination of Density - European Standards, n.d.), the three models were employed with a base measurement of 30x30 cm and thicknesses of 5, 2.5, and 1.8 cm. The models were heated in a conditioned room until reaching a constant weight. The thickness at the intersection of the diagonals were measured and the final mass and the edge measurements were determined. The equipment employed to perform the thermal conductivity test was a hot plate thermal conductivity meter, model EP500e, Version C, which allows measuring thermal conductivity from 0.002 to 2,500 W/m-K. The test performances were with a temperature range from 10°C to 40°C, with a temperature difference of 15°C between plates. In addition, each prototype test lengthens 60 minutes, and three 30x30 cm base samples used had a thickness of 5, 2.5, and 1.8 cm. Moreover, the specimens were immersed in water for 24 hours, measuring the mass before and after immersion.

Specimens with a base measurement of 30x15 cm were employed to determine the modulus of rupture in static bending (MOR) according to EN 310 [31]. Two supports bore the specimens, in which stress was applied in the midpoint length until reaching its fracture limit. Therefore, the compressive strength test was performed to determine the load-bearing capacity per unit area in terms of stress (kg/cm2). Samples measuring 15x12 cm were used in a Versa Tester 30M Soiltest universal machine with an operating range from 3000 to 15000 kg. Thus, the procedure verification consisted of a load ring with a resolution of 0.5 kg, which is hydraulic electric equipment graduated in kilogram force.

2.1. *Prototype I*

For the prototype I model, strips of banana pseudo-stem measuring 5 cm wide, 30 cm long, and 0.5 cm thick were used, placed on the outer faces of the prototype, keeping the whole peanut shells mixed with polyester resin inside them. For its elaboration, the strips of the pseudo-stem were cut in the same direction as the fibers and placed on the mold base one after another covering the entire surface (Figure 2A). Then, the first part of polyester resin was poured, in which the uncrushed peanut shells were deposited (Figure 2B). Later, the second portion of the resin was placed (Figure 2C) for a posterior sealing of the matrix with the pseudo-stem strips (Figure 2D). The last part of the resin embedded the latter. It was left it to harden for five days, supporting a weight of 50 kg for its consolidation (Figure 2E and 2F), depicted in Table 1.

Figure 2. Prototype I development.

Table 1. Percentage of composition of prototype I.

Materials	Measures (cm)	Amount (g)	Percentage (%)
Whole peanut shells		255.15	8.04
Banana fiber strips	5x30	226.80	7.15
Polyester resin	----	2691.15	84.81
Total	----	3173.10	100.00

2.2 Prototype II

For the second prototype, banana fiber was applied in strips that consisted of 0.5 cm wide and 30 cm long. Crushed peanut shells with a particle size of 0.5 cm were also used (Figure 3A, 3B, 3C and 3D), in which the elaboration consisted of the crushed peanut shell mixed with the polyester resin placed into the mold base. In the first layer, the banana fiber strips arrangement was vertically and horizontally, forming a central mesh pouring a portion of resin. Later, the prototype was sealed with a layer of crushed peanut shell mixed with resin. It was left to harden for five days with a 50 kg weight for consolidation. Then, a model of 30x30 cm with 2.5 cm thickness was obtained (Figure 3E and 3F), depicted in Table 2.

Figure 3. Prototype II development.

Table 2. Percentage of composition of prototype II.

Materials	Measure (cm)	Amount (g)	Percentage (%)
Pieces of peanut shells	0.5	283.50	13.89
Banana fiber strips	0.5x30	85.05	4.17
Polyester resin		1672.25	81.94
Total		2040.8	100

2.3 Prototype III

For this prototype, peanut shells and banana fiber were used in pieces of 0.5 x 0.5 cm in size (Figure 4A and 4B). In addition, a homogeneous mass was achieved by mixing the two chopped fibers with polyester resin in a container (Figure 4C and 4D). Then, it was placed slowly in the mold with hammer blows until reaching a thickness of 1.8 cm. It was left to harden for five days with a 50 kg weight for a later demolding. In the end, a model of 30x30cm with a thickness of 1.8cm was attained (Figure 4E and 4F), depicted in Table 3.

Figure 4. Prototype III development.

Table 3. Percentage of composition of prototype III.

Materials	Measure (cm)	Amount (g)	Percentage (%)
Peanut shell	0.5x0.5	283.50	40
Banana fiber	0.5x0.5	85.05	12
Polyester resin	---	340.25	48
Total		708.8	100

3. Results and discussion

3.1. *Density*

The density was determined by the relation of the mass and volume, based on its physical properties. Thus, the raw material density influences the material volume, the binder amount, the properties, and the finished surface. Moreover, changes in the prototype density caused changes in the physical and mechanical properties (Gatani et al., 2010).

Table 4. Density.

Prototype	Measure (cm)	Thickness (cm)	Density ρ (kg/m^3)
I	30x30	5.0	716.3
II	30x30	2.5	656.7
III	30x30	1.8	333.8

The resin dosage determines the density values. Nevertheless, the proportion between natural fibers and resin in lignocellulosic composites must be considered. Prototype I contains 85% resin and 15% natural fibers, and prototype II contains 82% resin and 18% fibers. These samples have a higher density than prototype III, consisting of 48% resin and 52% fibers. The density values give the physical and mechanical properties of each sample. The first two values are within the thresholds established in the EN 323 standard, with a range between 500 to 800 kg/cm^3.

3.2. *Absorption.*

The first two prototypes are within the range established by the regulations between 5% to 13% moisture absorption, compared to the third sample, which has an absorption value of 18.64% (Table 5). The latter is due to the higher resin dosage in the volume of the first two samples. It is worth mentioning that the first sample has a vast amount of resin in its interior because it consisted of whole peanut shells that leave voids between them, concerning the surface layers of pseudostem that are more exposed to moisture. The second prototype is more compact due to the smaller size of the fibers, maintaining a regular resin distribution.

Table 5. Absorption.

Prototype	Thickness (cm)	Starting weight P1 (kg)	End weight P2 (kg)	Absorption (%)
I	5.0	0.7336	0.776	5.77
II	2.5	0.4116	0.426	3.49
III	1.8	0.1888	0.224	18.64

3.3. *Thermal conductivity*

The thermal conductivity test based on the ISO 8302 standard depicts measures lower than 0.10 W/m·K, considered thermal insulating materials (Equation 1). As the fiber percentage in the samples increases, the thermal transmittance decreases, as it is seen in prototype III, depicted in Table 6.

$$k = \cdot \frac{\text{qx}}{T1 - T2} \quad (1)$$

k=thermal conductivity
e= thickness
T1= high temperature
T2=low temperature
qx=heat flux

Table 6. Thermal conductivity.

Prototype	Thickness (cm)	Measures (cm)	Weight (g)	Conductivity (W/m.K)
I	5.0	30x30	3173.1	0.093
II	2.5	30x30	2040.8	0.083
III	1.8	30x30	708.8	0.059

These results highlight the potential of these natural fibers for insulating material developments that contribute to the formation of thermally comfortable architectural spaces. Therefore, energy consumption can be optimized through artificial climatization, looking for solutions based on bioclimatic criteria. The process of obtaining the raw material will reduce environmental pollution, such as eutrophication (FAO, 2002) and the proliferation of dioxin by burning agricultural waste (Koul et al., 2022), due to poor waste management. The previous can lead to direct and indirect jobs based on a circular economy. The values achieved are interesting for future applications, considering the physical and mechanical capabilities described previously.

3.4. *Modulus of rupture in static bending*

The modulus of rupture (MOS) in bending is the maximum stress of the fibers in a failure moment (Equation 2). The MOR of the prototype is 72.8 kg/cm^2. This value is within the INEN standard/EN 312 (UNE EN 312:2010 Particleboards - Specifications - European Standards, n.d.), which admits minimum stress of 71.38 kg/cm^2 for structural boards used in dry environments, greater than 4mm thick. The second sample has a MOR of 145.6 kg/cm^2 according to the INEN standard, which admits a minimum value of 142.76 kg/cm^2, corresponding to structural boards used in humid environments with a thickness range of 20 to 25mm. In the second sample, the arrangement of the pseudostem fibers in strip forms, placed vertically and horizontally, contributed to the flexural breaking strength. Finally, the third prototypes did not comply with the values determined by the standard.

The fracture process, due to the polymeric nature of the matrix (partially deformable), originates progressively, with deformation and breakage of the polymer and internal tearing of the fibers (Figure 5). The lower resin content of prototype III means that the fractures of the specimens show less internal cohesion between the fibers after the tearing caused during the mechanical tests. Despite the different fiber dosage of prototypes I and II, the behaviour in compression tests was similar, due to a higher influence of the resin dosage as opposed to the influence of the nature of the fibers. In the flexural test, there is a higher influence of the fiber, although the fracture planes of prototypes I and II are similar, as can be seen in Figure 5.

$$MOR = \frac{3}{2} \cdot \frac{\mathrm{Pr} \cdot \mathrm{L}}{b \cdot h^2} \qquad (2)$$

MOR= modulus of rupture
Pr= load at rupture
L= support spacing
b= prototype width
h= prototype thickness

Table 7. Modulus of rupture.

Prototype	Thickness (cm)	Measure (cm)	Weight (g)	Max. load (kg)	MOR (kg/cm^2)
I	5	30x15	1716	700	72.8
II	2.5	30x15	1167.3	350	145.6
III	1.8	30x15	340.8	40	32.9

Figure 5. Image of the fracture plane of prototype I (A), II (B) and III (C).

3.5. Compression test

The compressive strength test was performed to determine the load-bearing capacity per unit area, expressed in terms of stress in units of kg/cm^2. As a test result, the relationship directly proportional to the density of the samples is evident. The prototype had a resistance of 23.89 kg/cm^2 with a maximum applied load of 4300 kg, the dose of resin contributes to the mechanical resistance. The test result of the second sample was not far from the first one, with a value of 20 kg/cm^2 based on an applied load of 3600 kg. Furthermore, the third sample, with a lower density and resin proportion, had a low compressive strength. Physical and mechanical properties are summarized in Figure 6.

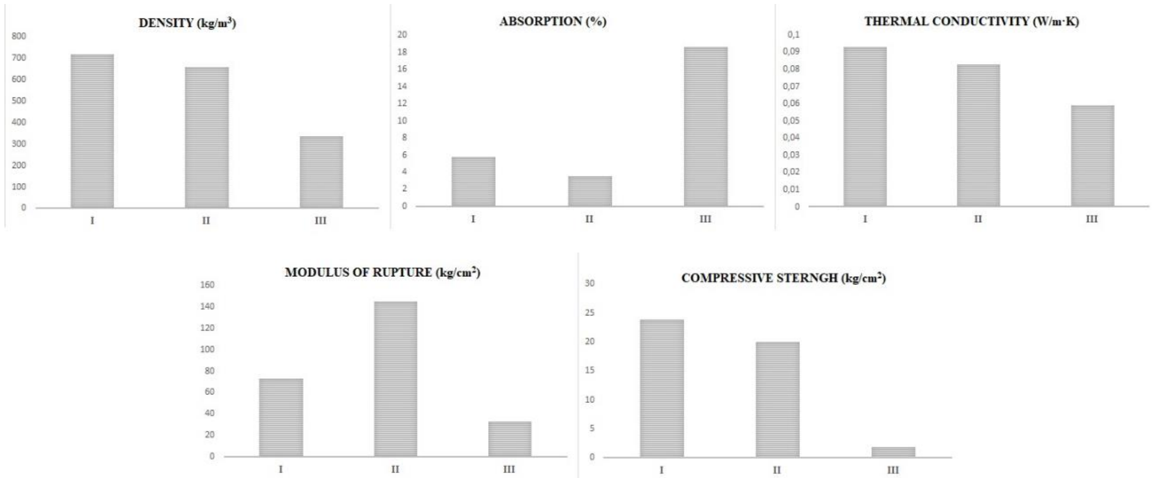

Figure 6. Physical and mechanical properties.

Table 8. Compressive strength test modulus of rupture.

Prototype	Thickness (cm)	Measure (cm)	Weight (g)	Max. load (kg)	Comp. strength (kg/cm^2)
I	5	15x12	1716.0	4300	23.89
II	2,5	15x12	1167.3	3600	20.00
III	1.8	15x12	340.8	300	1.80

4. Conclusions

The results depicted the potential of natural fibers as an insulator at different building elements and components. The insulating properties and the contribution they provide in the design of thermally comfortable spaces with a natural finished surface are highlighted, which depend on the application and shape of the product and also on the thickness and the dosage. Therefore, this research depicts the use of agricultural wastes in the innovation of materials for the construction industry. It leverages banana fiber and peanut shells conglomerated with polyester resin as a valid and eco-friendly alternative. Throughout our work, three prototypes were developed, in which the first and second obtained the best results in physical and mechanical tests according to standardized tests. It is worth noting its low thermal conductivity (0.09 to 0.08 w/m·k) in the hot plate test, which is a conductivity value lower than wood.

The processes carried out are part of a research to address a source of raw material agricultural waste, which is abundant worldwide, especially in countries based on a primary economy. Nowadays, waste material is one of the major pollutants that affect water resources. In addition, the use of organic material is expected to create jobs, reduce pollution by recycling, reduce energy consumption, and lead to projects of social interest to fulfill the objectives of sustainable development framed in the 2030 Agenda.

The fibers were not preprocessed through chemical treatments to improve mechanical strengths. Our purpose was to use and combine the organic matter in its natural state. For further tests, the fibers can improve by preprocessing. Moreover, it is recommended experimenting with other binders and varying the particle size for their compactness optimization. The authors will continue experimenting with the fibers, modifying dosages and conglomerates to allow the adaptability of the new products. The applicability could range from wall complements, roofing, room dividers, among other alternatives, considering its insulating capacity.

Author contributions: E. Eecheverría-Maggi: Conceptualization, Investigation, Formal analysis, Writing; V. Flores-Alés: Conceptualization, Investigation, Writing- review & editing, Supervision; J.J. Martín-del-Río: Conceptualization, Methodology, Formal analysis.

Conflicts of interest: The authors declare that they have no conflicts of interest.

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