Investigation of Crop Residues for Thermal and Acoustic Panel Production

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Abstract. The aim of this study is to protect forest resources and investigate the potential of using agricultural waste, namely crop residues, to produce thermal and acoustic particleboards. Agricultural resources commonly grown in Turkey, and corresponding wastes and byproducts, were examined. Corn stalk, corn cob and hemp hurds were selected to produce light-weight composite boards to be used as acoustic building panels. Experimental sets were prepared at 100% corn stalk, 100% corn cob, 100% hemp hurds and 100% wood. Urea-formaldehyde and tannin-based resins were selected as binders. The panel density was targeted at 400 ± 50 kg/m^3. Panel prototypes samples were prepared with a laboratory scale hot press. These samples were tested for their physical and mechanical properties according to European standards, including durability, thermal conductivity and the sound absorption coefficient. The results obtained show promising and competitive results when compared to literature and commercial boards, justifying further studies and boards scale-up.

Keywords: Biomass Composite · Lignocellulosic Materials · Insulation

1 Introduction

The current global challenges related to carbon emissions and climate change have drawn significant attention to green building concepts. These buildings emphasize the use of renewable natural resources to reduce overall carbon emissions and energy consumption. In residential, educational, and workplace buildings, noise control and acoustic comfort, thermal insulation and thermal comfort together with energy efficiency, and overall indoor environmental quality have become major societal concerns. Consequently, the demand for both acoustic and thermal insulation boards and solutions that are cost-effective, renewable, durable, healthy, and environmentally friendly is steadily increasing. This has led to a surge in research on alternative raw materials and the reuse

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and recycling of waste in the production of building insulation products, in line with sustainable development goals [1–3].

The growing demand for natural materials in the construction sector has increased pressure on forest resources, contributing to deforestation and biodiversity loss. To mitigate these impacts, it has become essential to explore alternative lignocellulosic sources—particularly non-wood materials and agricultural wastes and byproducts, namely those abundantly available in countries like Turkey, such as corn stalks, corn cobs, and hemp hurds [4].

Research shows that non-wood lignocellulosic materials can be effectively utilized in the production of particleboards and insulation products, offering comparable or even superior performance to conventional wood-based alternatives [1, 2, 5]. Moreover, the valorization of such residues supports circular bioeconomy principles by converting waste streams into value-added materials and reducing environmental footprints [4, 6, 7].

Numerous studies have evaluated the potential of agro-forestry industrial wastes in insulation board production, while efforts continue to develop more environmentally friendly adhesives such as tannin-based or low-emission urea-formaldehyde resins [8, 9]. Given the innovative nature of these materials, new testing methodologies have also been developed and refined [2, 3].

Given the significant environmental footprint of the building industry, greener alternatives, such as bio-based particleboards, can play a key role in reducing that impact. In particular, agricultural fibers like corn stalks have shown promising acoustic and thermal properties, making them suitable for insulation applications [10]. By incorporating these materials into construction products, it is possible to meet evolving technical standards while fostering sustainable resource utilization.

In this study, instead of obtaining wood from trees that grow in about 30–40 years, it is aimed to use agricultural wastes obtained annually for producing bio-based particleboards with promising acoustic and thermal properties, underscoring their potential as sustainable building materials and affirming the role of non-wood lignocellulosic resources in minimizing the environmental impact of the construction sector. Beyond their renewable resource potential, agricultural wastes represent a significant waste stream that is often underutilized or inadequately managed, leading to environmental problems such as open-field burning, greenhouse gas emissions, and soil nutrient depletion. By incorporating these residues into building materials, it is possible to mitigate such environmental impacts, reduce disposal costs, and decrease the reliance on landfilling or incineration. This valorization approach aligns with circular bioeconomy and waste hierarchy principles, in which agricultural waste is transformed into value-added construction materials, contributing simultaneously to waste minimization, resource efficiency, and climate change mitigation.

Due to the impact of the building industry, and the importance the use of greener particleboards can have on reducing that impact, the aim of this study is to protect forest resources and investigate the potential of using agricultural waste, namely crop residues, to produce thermal and acoustic particleboards.

2 Materials and Methods

2.1 Materials

The feasibility of using crop residues as an alternative to wood in particleboard manufacturing was evaluated. Raw material selection was based on the prevalence and availability of agricultural waste in Türkiye. Corn, as one of the most extensively cultivated crops in the country [11], was identified as a key lignocellulosic source; therefore, corn stalks and corn cobs were incorporated into the experimental design. Hemp hurds were also included, as hemp is a renewable natural low-density resource with good mechanical properties, and can be found as a byproduct of the textile industry. Therefore, its use aims to enhance both the thermal and mechanical performance of the panels. Additionally, this approach supports industrial symbiosis by valorizing cross-sectoral residues and contributes to the environmental sustainability of the bio-based boards.

The three lignocellulosic raw materials - corn stalks, corn cobs, and hemp hurds - were used to produce lightweight composite panels intended for acoustic and thermal insulation applications. All materials were obtained from agricultural production areas across Türkiye. Before panel fabrication, the residues were mechanically processed and classified to a standardized particle size suitable for laboratory-scale board production. The dimensions of the particles used are in the range of 2.1–0.7 mm sieve. Four experimental groups were prepared, each composed of a single raw material: 100% corn stalk, 100% corn cob, 100% hemp hurds, and 100% wood particles, the latter as control group for comparison (Fig. 1).



Fig. 1. From left to right, cut wood particles and hemp hurds, corn cob before preparation and cut corn stalk.

Two binders were utilized: a urea-formaldehyde (UF) glue, representing conventional synthetic binders (Kastamonu Entegre, Türkiye), and a tannin-based bio-binder, sourced from NTE / Bondtite (South Africa). The selection of the binder systems was based on their relevance to both traditional and bio-based particleboard technologies, with particular attention paid to emission profiles and environmental compatibility. Their properties are presented in Table 1.

2.2 Production of the Particleboard Samples

The target density for all boards was set at 400 $\pm$ 50 kg/m^3, suitable for acoustic and thermal insulation applications. Laboratory-scale prototypes were produced using a 500 $\times$ 500 mm^2 hot press, with a nominal panel thickness of 16 mm. The conventional UF

resin was used for reference board production, reflecting common industrial practice. To evaluate a more environmentally sustainable alternative, the tannin-based bio-resin was also employed. For both resin types, the adhesive was applied at a loading level of 12% based on oven-dry particle weight. A laboratory-scale spray gluing system was operated to apply the glue uniformly to the particles prior to mat formation and hot pressing. In this context, particleboard prototype production stages are given in Fig. 2.

Table 1. Properties of the adhesives used.

Properties	UF (1.22 mol)	Tannin
Solid (%)	65 ± 2	47
Density (g/cm^3)	1270–1295	1215
pH (25 °C)	7.8–9	6.47
Viscosity (cP 20 °C)	100–600	200
Gel point (sn, 100 °C)	35–45	110

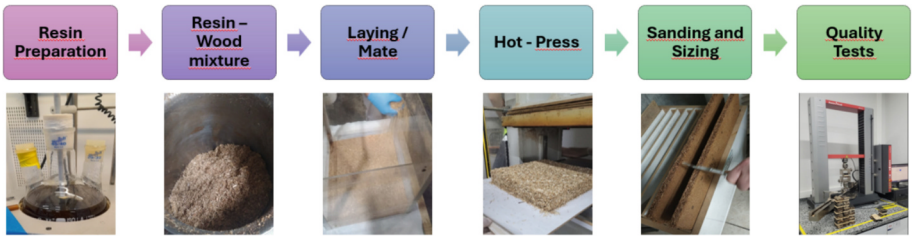


Fig. 2. Particleboard prototype production stages

Experimental design for the production of the particleboards is given in Table 2. Press parameters applied in particleboard production are given in Table 3.

Table 2. Particleboard prototypes experimental design.

Board type	Lignocellulosic material	Adhesive type	Adhesive content (%, wt)
WU	Wood	UF	12
WT	Wood	Tannin	
HU	Hemp hurds	UF	
HT	Hemp hurds	Tannin	
CSU	Corn stalk	UF	
CST	Corn stalk	Tannin	

(*continued*)

Table 2. (*continued*)

Board type	Lignocellulosic material	Adhesive type	Adhesive content (%, wt)
CCU	Corn cob	UF	
CCT	Corn cob	Tannin	

Table 3. Hot- press parameters for the particleboards prototype production.

Temperature	Pressure	Pressure time
215 °C	80 bar	4:05 (min)

2.3 Test Methods and Samples

Test samples were prepared and tested according to EN standards. For some tests, additionally to the innovative particleboards developed, samples of commercial particleboard and MDF were also tested for comparison. The samples were conditioned at 60 ± 5% relative humidity and at a temperature of 23 ± 2 °C prior to tests, until constant mass. The prototypes were tested physically and mechanically according to specification for particleboards, defined by EN 312 [12]. The average value of five samples were tested for each property, except when something contrary is mentioned. The following tests were performed:

- Density, based on EN 323 [13];
- Thermal conductivity, using a portable ISOMET 2114 with an IPS1105 surface probe with 60 mm diameter and measurement range 0.04–0.3 W/(m K); the measurements were performed with the samples in controlled laboratory conditions of temperature (T) and relative humidity (RH): lower RH, at 18.3 ± 0.8 °C and 47.6 ± 2.9%, and higher RH, at 18.5 ± 0.6 °C and 67.6 ± 5.4%; three measurements were made per particleboard type; the average and standard deviation are considered (Fig. 3a);
- Sound absorption coefficient using the impedance tube - transfer function method, based on ISO 10534-2 [14]; this test was just performed with the particleboards produced with tannin glue;
- Internal bond, based on EN 319 [15];
- Bending strength and Elasticity modulus, based on EN 310 [16];
- Surface soundness, based on EN 311 [17].

The samples were produced as boards with circa 20 cm × 20 cm × 2 cm. They were used for non-destructive tests and then cut into smaller specimens for the different tests. The samples tested for acoustic properties are circular (Fig. 3b), with 99 mm diameter and 16 mm thickness.



Fig. 3. A particle board being tested for thermal conductivity, with the ISOMET equipment and on top of expanded cork board to insulate from the table, and circular samples for the acoustic test.

3 Results and Discussion

3.1 Physical Properties

The density of the boards is given in Fig. 4. Results were obtained within the target value range of 400 ± 50 kg/m^3 and variations are low between all tested particleboards.

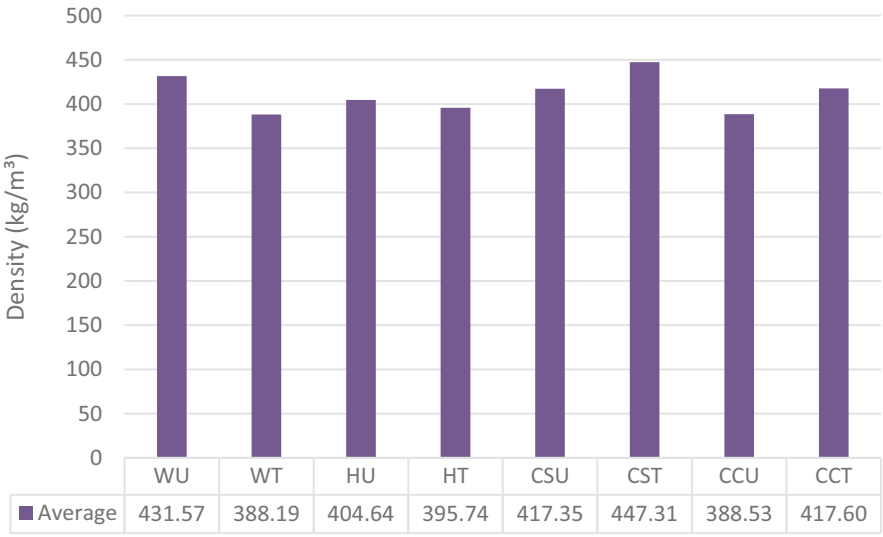


Fig. 4. Test results of density of the particleboards with wood (control), hemp, corn stalk and cob, with UF and tannin glues.

The difference in densities between UF- and tannin-bonded panels can be explained by the combined effects of adhesive viscosity and the porous structure of the lignocellulosic particles. In wood-based panels, the UF adhesive—with lower viscosity—penetrates more effectively into the relatively uniform and compact wood particles, enabling better particle compaction during pressing and resulting in higher density. In contrast, the

agricultural residues, such as corn stalk and cob, have a more porous and heterogeneous structure, which allows UF resin to penetrate excessively and unevenly, reducing mat stability and compaction during pressing and thus leading to lower density. The tannin-based adhesive, having higher viscosity, tends to remain more at the surface of these porous particles, improving mat cohesion and compaction, and therefore resulting in higher final panel density. Additionally, slight deviations related to laboratory-scale hot-press equipment—including temperature distribution and pressure homogeneity—may have contributed to the observed variations in panel density.

The thermal conductivity (average and standard deviation) is presented in Table 4, for lower and higher RH. Additionally to the innovative particleboards developed, commercial particleboard and MDF were also tested for comparison.

Table 4. Thermal conductivity (average and standard deviation) for commercial particleboard, MDF and the developed boards.

Board	Thermal conductivity [W/(m K)]			
	Lower RH		Higher RH	
	Ave.	Stdv.	Ave.	Stdv.
Ref PB	0.116	0.002	0.121	0.002
Ref MDF	0.110	0.001	0.114	0.001
WU	0.074	0.003	0.076	0.002
WT	0.075	0.003	0.078	0.002
HU	0.073	0.004	0.074	0.004
HT	0.088	0.002	0.089	0.002
CSU	0.075	0.001	0.078	0.002
CST	0.086	0.003	0.089	0.002
CCS	0.076	0.002	0.078	0.001
CCT	0.088	0.001	0.091	0.000

Results show that all tested boards present very low standard deviation. As expected, the thermal conductivity when the boards are conditioned at lower RH is lower than at higher RH, although for some boards the difference is very low and within the standard deviation. The control wood-UF board has a thermal conductivity very similar to the wood-tannin board, both at lower and higher RH. Comparing the boards with corn cob, corn stack and hemp, the boards with UF have lower thermal conductivity than the similar boards with the tannin glue. However, and as intended, all the innovative particleboards have significantly lower thermal conductivity than the commercial MDF and particleboards. Analysing available literature, Abobakr et al. [18], testing particleboards produced with rice husk and epoxy resins achieved thermal conductivity values ranging from 0.064 to 0.076 W/(m K). Faria et al. [19], testing particleboards produced with bean straw and rubberwood particles glued with vegetable polyurethane adhesive registered thermal conductivity ranging from 0.097–0.106 W/(m K). Essid et al. [20], testing flax

shives particleboards with lignin and epoxy resin glues, reached thermal conductivities of 0.074–0.081 W/(m K). Comparing with literature and commercial boards, it can be concluded that the boards developed in the present study are competitive and can have a positive effect on energy efficiency.

Noise is an important problem in residential and workplaces in urban areas. The demand for acoustic solutions which are cost-effective, renewable, eco-friendly in nature is increasing. Figure 5 shows the graph of the sound absorption coefficient measurements of the boards produced with the four biomasses and tannin glue. The acoustic tests were conducted using the same particleboard specimens that were characterized for thermal and mechanical properties. Therefore, the thickness and density values of the test specimens correspond to those provided earlier in the Materials and Methods and Results sections. Specifically, the circular samples used for the acoustic tests had a diameter of 99 mm and a thickness of 16 mm, with density values within the target range of 400 ± 50 kg/m^3 as shown in Fig. 4.

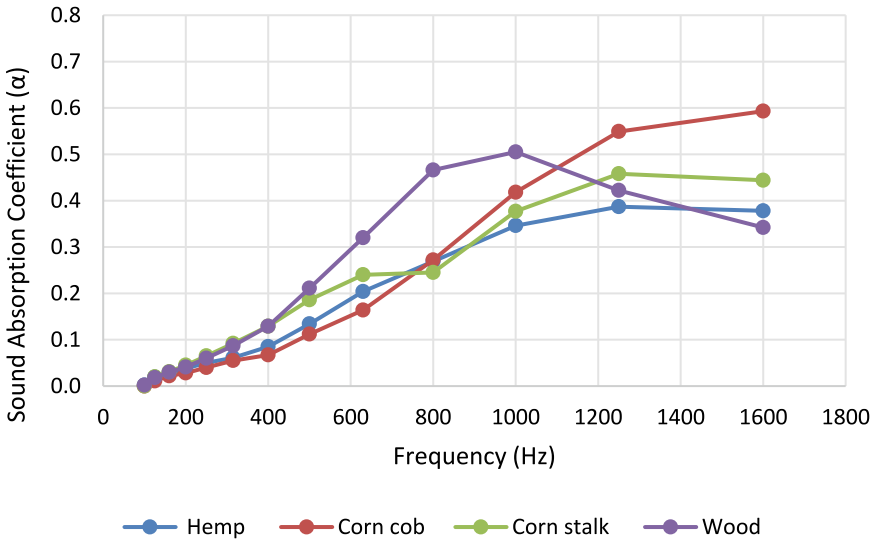


Fig. 5. Sound absorption coefficient in function of the frequency for the boards with hemp, corn cob, corn stalk and wood with tannin glue.

It can be seen that, for frequencies above 1100 Hz, the best result belongs to the corn cob-based boards, followed by the hemp-based ones, both better than the control wood-based board. The latter is better for frequencies between 500 Hz and 1100 Hz.

3.2 Mechanical Properties and Durability

The results obtained from the internal bond tests of the boards are given in Fig. 6. It can be observed that the hemp boards, both with UF and tannin glues, present the higher internal bond. The corn cob boards present intermediate values, while the boards with corn cob are the lowest ones. The tannin significantly reduces the internal bond of the

control wood particle board and the hemp-based board. But the tannin glue slightly increases the internal bond for the corn stalk board and particularly the corn cob board, which is clearly positive.

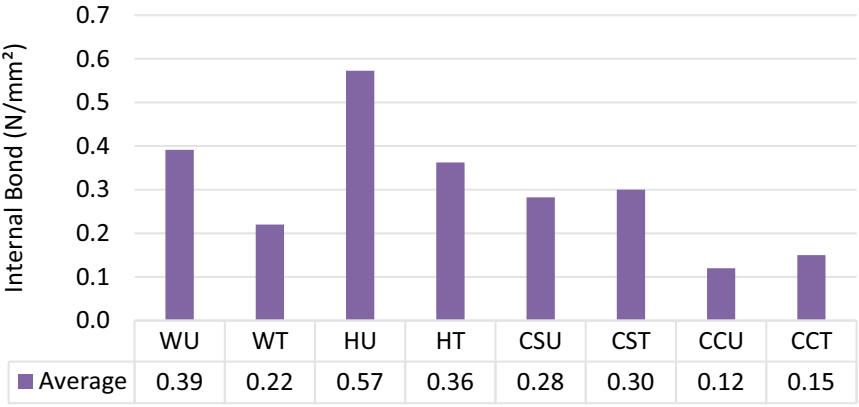


Fig. 6. Test results of internal bond of the particleboards with wood (control), hemp, corn stalk and cob, with UF and tannin glues.

The results obtained from the bending strength tests of the boards are given in Fig. 7. It can be observed that the bending is higher for the hemp-based boards, followed by the corn stalk ones, the latter also competitive in comparison to the control wood-based boards. Again, the corn cob boards have the lowest results of bending strength. The tannin glue significantly reduces the bending capacity of the control wood particleboard, but not so much for the hemp-based and even less for the corn stalk board. The tannin glue is beneficial for the corn cob board, which is in accordance with the internal bond results.

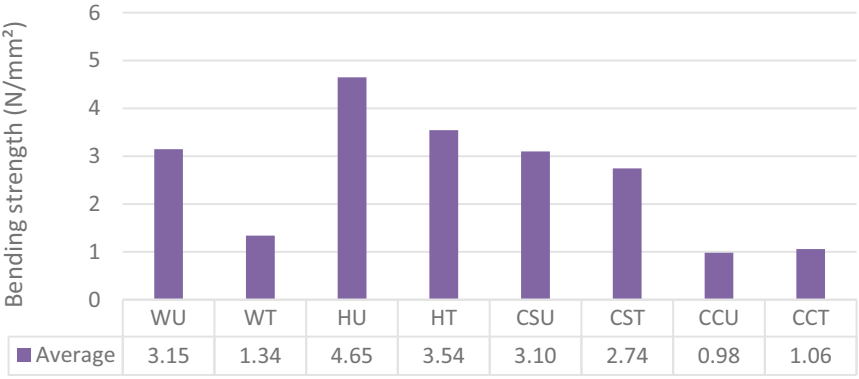


Fig. 7. Test results of bending strength of the particleboards with wood (control), hemp, corn stalk and cob, with UF and tannin glues.

In Fig. 8, elasticity modulus test results are given. Accordingly, the test results of hemp-containing boards with both glues are higher than those of boards produced from other lignocellulosic sources, while the ones with corn cob present the lowest values. Again, the corn stalk boards present competitive performance when compared to the control wood-based boards.

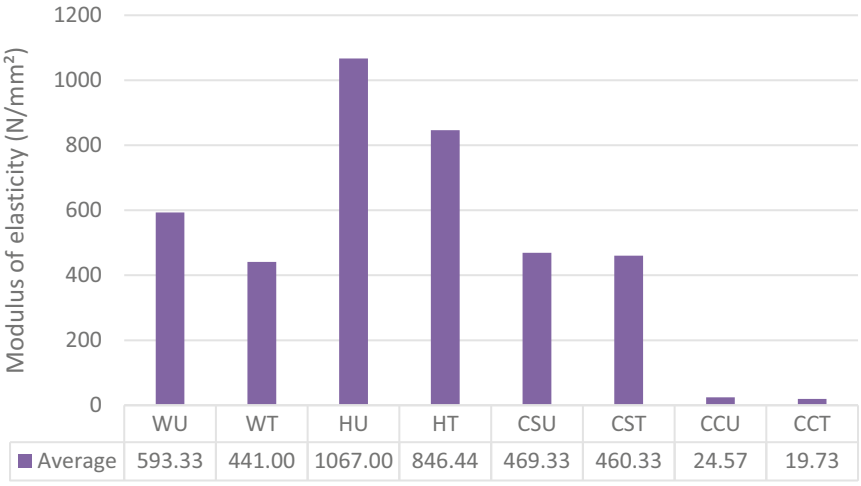


Fig. 8. Test results of modulus of elasticity of the particleboards with wood (control), hemp, corn stalk and cob, with UF and tannin glues.

Figure 9 shows the results of the surface durability tests. According to these results, the durability of hemp-containing boards is always higher than those of other tested particleboards. There is a decrease of strength when using tannin glue instead of the UF one, but that is higher for the control wood-based boards and lower for the hemp and corn stalk boards. The tanning glue seems very positive for the corn cob board, showing a high durability in comparison to the UF when using this biomass.

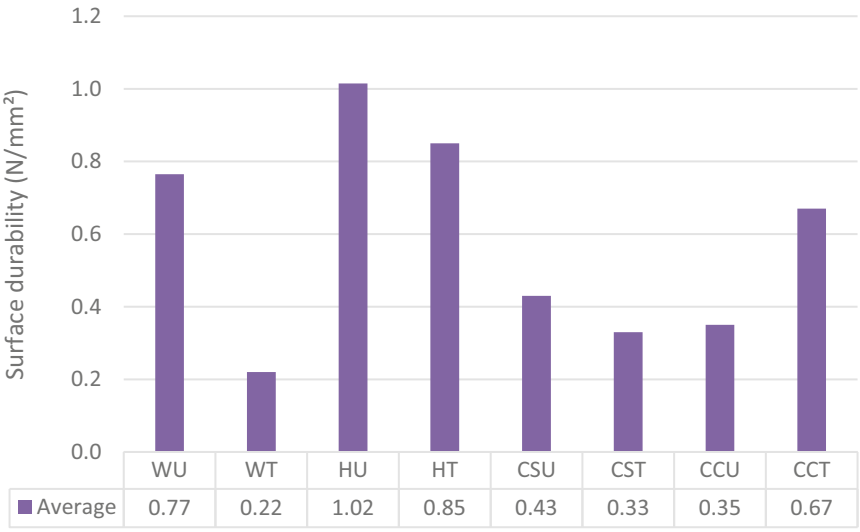


Fig. 9. Test results of surface durability of the particleboards with wood (control), hemp, corn stalk and cob, with UF and tannin glues.

4 Conclusions

It is important to reduce harvest pressure in face of increasing wood demands. The aim of this study is to protect forest resources and investigate the potential of using agricultural waste in the insulation panel industry instead of fossil-based materials.

Agricultural resources and waste byproducts commonly grown in Turkey were examined. Corn stalk, corn cob and hemp hurds were selected to produce lightweight composite boards to be used as acoustic and thermal insulation panels. Experimental sets were prepared at 100% corn stalk, 100% corn cob, 100% hemp hurds, and 100% wood as control for comparison. Urea Formaldehyde and tannin-based resins were selected as binders. The boards density was targeted at 400 ± 50 kg/m^3 and prototypes were prepared with a laboratory scale hot press, and tested for their physical and mechanical properties according to European Norms, including the sound absorption coefficient and thermal conductivity.

As a result of the tests, it was seen that the chosen crop residues have potential to be used as a substitute for wood for particleboards production. For thermal conductivity all the crops tested were viable and with lower values in comparison to commercial particleboards and MDF. The most positive results in terms of acoustic tests were obtained with corn cob-based particleboards.

Results justify further investigations. Therefore, for complementary characterization and numerical simulation of the effect these panels can have when used indoors, additional experimental sets are made using tannin-based resins made of lignocellulosic residues. By integrating agricultural waste into durable construction materials, this approach helps to reduce the environmental burden of residue accumulation, including minimizing greenhouse gas emissions from open-field burning and reducing soil nutrient loss. The carbon present in lignocellulosic biomass can be effectively sequestered

within the panels, acting as a carbon sink during their service life. Additionally, the replacement of petrochemical-based adhesives with bio-based binders such as tannin resins lowers the emission of formaldehyde and other volatile organic compounds, thus improving indoor air quality and reducing toxicity. Beyond material efficiency, promoting hemp cultivation contributes to biodiversity, improves soil regeneration, and supports low-impact agricultural systems. These synergies address multiple United Nations Sustainable Development Goals (SDGs), including responsible consumption, climate action, and sustainable communities.

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