Effect of Density on Acoustic and Thermal Properties of Low-Density Particle Boards Made from Agro-Residues: Towards Sustainable Material Solutions

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This study assessed the feasibility of using major agricultural residues specifically bagasse, rice straw, wheat straw, and coir fiber to produce single-layer particle boards. These boards of densities 300, 400, and 500 kg/m³ were developed using melamine urea formaldehyde resin. Comprehensive evaluation of the boards included determination of their sound absorption coefficient (SAC), thermal conductivity, and noise reduction coefficient (NRC), as well as various physical properties and modulus of rupture. Additionally, the impact of board density on the SAC across a frequency range of 50 to 5000 Hz was examined. The coir boards displayed superior SAC, particularly at 3000 Hz. Rice straw boards at a density of 300 kg/m³ exhibited the lowest thermal conductivity (0.098 W/m-K). Density of 300 kg/m³ was optimal for achieving the highest SAC and lowest thermal conductivity in agro residue particle boards. As the density of the boards increased, SAC decreased, whereas thermal conductivity (K) increased, indicating that lower-density boards are more effective as sound and thermal insulators. Furthermore, all particle boards demonstrated promising sound absorption capabilities, achieving classifications of D and E under ISO 11654:1997, making them viable for interior applications in the building industry.

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INTRODUCTION

To minimize external noise, ensure a comfortable indoor temperature, improve health benefits, and to enhance comfort and privacy, sound and thermal insulation plays a crucial role in human dwellings. Most of the currently used construction methods use synthetic materials for sound and thermal insulation applications. Though these synthetic materials perform satisfactorily, not only are they non-biodegradable, but they also require enormous amounts of energy during production, emitting harmful gases into the atmosphere, thereby contributing to carbon emissions and global warming (Chen *et al.* 2024; Senthilkannan Muthu 2020). Construction practices have historically had a substantial impact on carbon footprints, threatening environmental sustainability. In response, governments and organizations worldwide are implementing policies aimed at achieving carbon neutrality. Various countries have taken initiatives, including the "European Green Deal," launched in 2019 by the European Commission. The United States has committed to carbon neutrality in federal operations by 2050, while China aims to achieve carbon neutrality by 2060. In this context, India has focused on its National Action Plan on Climate Change (NAPCC) and the Green Rating for Integrated Habitat Assessment (GRIHA), which mandates sustainable building practices and incentivizes the use of eco-friendly materials and technologies.

The quest for sustainable building materials is gaining significant momentum, driven by the need to reduce environmental impact and promote resource efficiency. One of the most used renewable materials as sound absorber is wood in the form of panels or particle boards (Bertolini *et al.* 2019). However, the shortage of wood resources has motivated researchers to find ways to replace wood with other lignocellulosic materials. These lignocellulose-based materials have demonstrated their promise for sustainability, energy efficiency, and a beneficial environmental effect in the construction sector (Raza *et al*. 2024). Because of their exceptional insulation and structural properties, these materials have shown not just viability but also tremendous potential for carbon-neutral building (Chen *et al.* 2024). Generally, lignocellulose materials such as wood/plant/agro materials are porous in nature, which is expected for a good insulation material. India, being an agrarian country, has rich sources of agro residues which needs to be utilized to their full potential. Each year around 141 million tons of crop residue is generated in India which ensures promising raw material for both commercial and construction uses (Gatkal et al. 2024). These natural fibers, which are mostly composed of cellulose, hemicellulose, and lignin, have constant physical properties, which makes them appealing for use in environment friendly building techniques (Nasri *et al.* 2023). Converting agro residues and lignocellulose materials into flakes, slivers, shavings, splinters and granules, then mixing them with a binding agent and pressing them under controlled temperature and pressure, results in particle board (Laufenberg *et al.* 1984; Krug *et al.* 2023). Its advantages, such as increased porosity and cost-effectiveness compared to wood, make it a suitable option for low-density building applications (Karlinasari *et al.* 2012). Particle boards are classified into three categories depending upon the density, low density particle boards ($\leq 400\ kg/m^3$), medium density particle boards (500 to 900 kg/m^3), and high density particle boards ($\geq 900\ kg/m^3$). Depending on the density of the particle board, its performance and suitability for various applications are determined. Lower density boards are often preferred for acoustic and thermal applications in theaters and auditoriums, office spaces, music rooms, sound recording studios, commercial and residential buildings, including prefabricated modular homes. The sound-absorbing capacity of particle board is measured by its sound absorption coefficient (SAC) in acoustics, while its overall sound absorption performance is rated by the noise reduction coefficient (NRC). Additionally, lower thermal conductivity indicates the material's effectiveness as an insulator. Further, particle boards should possess not only good acoustic and thermal properties but also strong structural integrity.

Further, these lignocellulosic materials are environmentally friendly, cheaper, and light weight. These favorable attributes have motivated researchers to explore the development of sustainable construction materials targeting acoustic and thermal applications. Such studies have involved rice straw (Sampathrajan *et al.* 1991; Hussein *et* *al*. 2019), wheat straw (Ali *et al*. 2020), sugarcane bagasse (Loh *et al.* 2013; Malawade and Jadhav 2020), coir fiber (Sampathrajan *et al.* 1991; Khedari *et al.* 2003; Nor *et al.* 2010; Bhingare and Prakash 2020), sunflower stalks (Mati-Baouche *et al.* 2014; Abbas *et al.* 2021), jute (Wang *et al.* 2024), hemp (Ouakarrouch *et al.* 2022; Song *et al.* 2024), rice husk (Marques *et al.* 2021), corn cob (Sampathrajan *et al.* 1991), bamboo (Karlinasari *et al.* 2012; Nath *et al.* 2011), kenaf (Sambu *et al.* 2016; Selvaraj *et al.* 2024), flax (Dhanakodi *et al.* 2023; Song *et al.* 2024), fruit stones (SheikhMozafari *et al*. 2024), groundnut shell (Sampathrajan *et al.* 1991), grass (Abobakr *et al.* 2024; Ye *et al.* 2024), sisal (Carvalho *et al.* 2015; Dunne *et al*. 2017; Martins *et al.* 2021), oil palm (Istana *et al.* 2023; Kalaivani *et al.* 2017), date palm (Khidir *et al*. 2014) and luffa (Koruk *et al.* 2022), *etc*.

Absorption panels were developed using rice husk and bagasse as raw material bond with Phenol-Formaldehyde (PF) adhesive. Different compositions with ratios 0, 25, 50, 75, and 100% were studied. It was found that 100% rice husk panels had higher sound absorption coefficient compared to other panels because of the spongy properties of rice husk that created many void spaces, resulted in more absorption (Zuhaira Ismail *et al.* 2015). Ferrandez-Villena *et al*. (2022) investigated the thermal and acoustic characteristics of particle board composed of mulberry pruning residues in different particle sizes and urea formaldehyde (UF) as an adhesive and average densities of the boards ranged between 848 and 807 kg/m^3. According to the findings, the raw material's particle size (0.25 to 1 mm) affected the acoustic qualities but did not affect thermal conductivity. The acoustic and thermal performance of luffa fiber panels is greatly affected by their thickness and density, whereas the binder content has minimal influence. The optimum conditions for fabricating panels was as follows: 40 mm thickness, 225 kg/m^3 density, and 7.5% binder content (Halashi *et al.* 2024). Karlinasari *et al.* (2012) studied the acoustic properties of particle board made from betung bamboo of densities 500 and 800 kg/m^3 with three particle sizes fine (particles passing 10 mesh sieve), medium (length 10mm X width 2 to 3 mm X thickness 0.5 mm), and wool (length 50 mm X width 3 to 4 mm X 0.2 to 0.5 mm thickness) bonded using isocyanate resin. Results suggested particle boards produced with fine and medium sized particles had better SAC than boards made with wool particles (Karlinasari *et al.* 2012). The thermal and acoustic performance of flax fiber is significantly influenced by the fiber size produced through grinding methods. Larger fiber sizes enhance acoustic performance, while smaller fiber sizes demonstrate better thermal resistance (Hajj *et al.* 2011; Song 2017; Wang *et al.* 2024). An insulation bio-based composite with a thickness of 12 mm was developed using sunflower stalk particles and chitosan solution as a binder, with varying compaction pressures. The results indicated that both thermal and mechanical performances improved with increased compaction (Mati-Baouche *et al.* 2014).

Yang *et al.* (2003) demonstrated the use of rice straw as a partial replacement for wood particles in particle board production. The resulting particle boards, made from a mixture of rice straw and wood particles at densities of 400 and 600 kg/m^3, outperformed conventional wood-based materials with respect to acoustic properties. A study on composite particle boards, which were created from oil palm fronds utilizing urea-formaldehyde (UF) resin as a binder, found that the absorption coefficient increased significantly with a decrease in bulk density (Istana *et al.* 2023). Khidir *et al.* (2014) investigated date palm panels with varying densities using palm fibers. Panels of 77, 100, and 125 kg/m^3 were produced. The results showed that both the absorption coefficient and noise reduction coefficient increased with the density of the panel. Ali *et al.* (2020) developed an insulation material using *Eucalyptus globulus* leaves and wheat straw fibers with corn starch as the adhesive. Four hybrid samples were developed with varying densities and compositions. The thermal conductivity ranged from 0.045 to 0.055 W/m-K, while the sound absorption coefficient (SAC) values exceeded 0.5 in the frequency range of 500 to 1600 Hz. The results indicated that eucalyptus leaves can serve as a promising material for insulation applications with low environmental impact. Nor *et al.* (2010) examined the effects of various factors on the acoustic performance of coir fiber samples bound with latex and the results indicated that fiber diameter and layer thickness significantly influenced sound absorption, while the panel's bulk density had a minimal effect. Additionally, the study presented approaches to enhance acoustic absorption through modifications in physical components, showing that well-selected fibers combined with an optimal bulk density can improve sound absorption. In other work, Kalaivani *et al.* (2017) examined how the thickness of oil palm trunk fiber boards affects their acoustic properties. Using UF resin, fiber boards with thicknesses of 8, 12, and 16 mm and an average density of 200 kg/m^3 were produced. Results showed that the thinner 8 mm fiber board achieved a higher sound absorption coefficient (SAC) across a broad frequency range of 3000 to 6000 Hz, suggesting that oil palm trunk fiber is a promising material for sound absorption applications.

To summarize, agro residue particle boards offer a promising avenue for the development of sustainable construction materials. The literature survey presented above advocates the manufacturing of particle boards of density more than 500 kg/m^3 using various agro residues either individually or in combination with other lignocellulose materials. Some studies have been conducted without using any binder material, focusing solely on acoustic properties rather than mechanical properties. These materials meet acoustic requirements but lack structural capabilities. Several studies have explained the significance of particle size and panel thickness on its performance. However, the mechanical, thermal, and acoustic performance of lower density (300 to 500) kg/m^3 panels developed from different agricultural waste is not yet clear. Also, limited data availability on agro residue particle board is hindering their usage as thermo-acoustic building material. Thus the study in this area may reveal the possibility of efficiently utilizing agricultural residues in construction applications, supporting the broader goals of sustainability and carbon neutrality in the building sector. In this context, the authors investigated the effect of density on the performance of 12-mm particle boards made of agro residues such as rice straw (RS), bagasse (BG), wheat straw (WS), and coir (COIR) for acoustic and thermal applications along with physical and mechanical properties. The study also aimed to determine the potential of the above-mentioned agro residues in panel manufacturing intended for building applications.

Following the introduction, the paper details the materials and methods used in the study. It begins by describing the collection and processing of four types of agro residues into particles including their chemical analysis, the manufacturing process of the particle board is outlined, along with the specific formulations used for the study. Next to be described are methods of testing, which include Modulus of Rupture (MOR), surface absorption swelling, water absorption, Sound Absorption Coefficient (SAC), Noise Reduction Coefficient (NRC), and thermal conductivity according to standard procedures. The findings and discussions are presented in the last section, followed by conclusions that summarize the results and their implications for future research.

EXPERIMENTAL

Materials and Methods

Preparation of particles

Agro-waste materials, such as rice straw, bagasse, wheat straw, and coir, were utilized in the development of low-density particle boards. The RS obtained from Bidadi, Karnataka, India were chopped to a required size of 20 cm. Subsequently, it was fed to a hammer mill for further size reduction of the particles. The RS initial moisture content was between 14 to 15%. Next, using an industrial air-circulated hot air oven, the RS was dried until it reached a moisture content of 6 to 8%. Following the drying process, the RS was fed through a pulverizer to further decrease the particle sizes. The pulverized particles were sifted through a sieve to separate particles measuring 2 to 3 mm in length and fine dust particles, constituting approximately 0.2 to 0.3% on a dry basis. BG was sourced from a sugar factory in Shimogga district, Karnataka, India. The material underwent a drying process to achieve a moisture content of 10% at 60 ± 2 °C, utilizing an industrial air-circulated hot air oven. Pith was removed from the BG by a depithing process. Subsequently the depith BG was hammer-milled to generate particles of required sizes. Further particles were gathered and sieved. Particles with lengths ranging from 1.5 to 3.0 mm were used to make the BG particle boards. WS, obtained from Nalagund in North Karnataka, India had a moisture content ranging from 20 to 25%. The WS particles measuring 2 to 3 mm in length were used in their original form for board production. Coconut coir, a lignocellulosic natural fiber, was sourced from M/s Coir Institute for Coir Technology, Peenya, Bangalore, Karnataka, India. The coir fiber was sun-dried till it reached a moisture content of 3 to 4%. Using an ASTM Sieve (No. 7), the coir was sieved to recover a particle size of 2 to 3 mm. Any coir fibers above 5 mm were subsequently pulverized to attain the required size. All of these agro residues were subjected to chemical analysis *viz*. lignin, ash, and silica content. The lignin was determined by the Ross Potter method (Ross and Potter 1930). Ash and silica were determined by standard procedures. The chemical analysis results are tabulated in Table 3.

Synthesis of Resin & Adhesive Formulation

Melamine urea formaldehyde resin (MUF) was used as the binder for particle board preparation. The MUF resin, with a weight ratio of 1:2 (0.5 M + 0.5 UF), was synthesized using formalin (37% aldehyde content), as well as urea and melamine with 46% and 67% nitrogen content, respectively. The resin synthesis took place in a three-necked glass kettle with a capacity of 2 liters. Initially, 600 g of formalin (37% formaldehyde content) was added to the resin kettle. Upon adjusting the formalin's pH from 8.5 to 9.0, stirring was started. The resin's pH was fine-tuned with a cooled sodium hydroxide solution (33% w/w). Subsequently, 150 g each of melamine and urea were introduced into the kettle with uninterrupted stirring. The pH was again accustomed from 8.5 to 9.0 after the addition of urea and melamine. Heat was applied to the resin kettle to reach a temperature of 85 °C, maintaining it at 85 ± 2 °C, and concurrently sustaining the pH at 8.5 to 9.0. The condensation reaction continued until the water tolerance of the resin reached 1:4. The resin was subsequently cooled to room temperature and discharged. Once it had fully cooled, it was kept in an airtight container at room temperature. Such a resin mixture has a shelf life of 2 to 3 weeks when kept at 25 ± 2 °C. When utilized for board manufacturing, the resin had a pH of 9.0 and a flow time of 19 seconds. The resin's water tolerance was found to be 1:2.5 and its solids content was measured at 52.3% when employed in the manufacture of particle board. The melamine urea formaldehyde resin was blended with ammonium chloride as a hardening agent, liquor ammonia as a buffering agent, and wax as a sizing agent. The adhesive formulation for 100 parts of liquid MUF resin in percentages is detailed in Table 1.

Table 1. Adhesive formulation Used for Manufacturing of Boards

SI No	Particulars	Percentage (%)
1	MUF resin	100
2	Hardener	0.4
2	Water	Twice the hardener
3	Buffer	1.0
5	Wax	1.0

Manufacturing of Particle board

The BG, COIR, RS, and WS particles were dried to a moisture content of 3 to 4% before being mixed with the adhesive. A combination of these particles and 10% resin on a dry solid basis was used as per the formulation of boards in Table 2. The consolidated particles were shaped using a mat-forming box with base dimensions measuring 330 mm × 330 mm. A wooden plate was physically pressed on the mat to prepress and compress the particles in the mat forming box. Spacers were placed on either side to maintain the thickness of 12 mm.

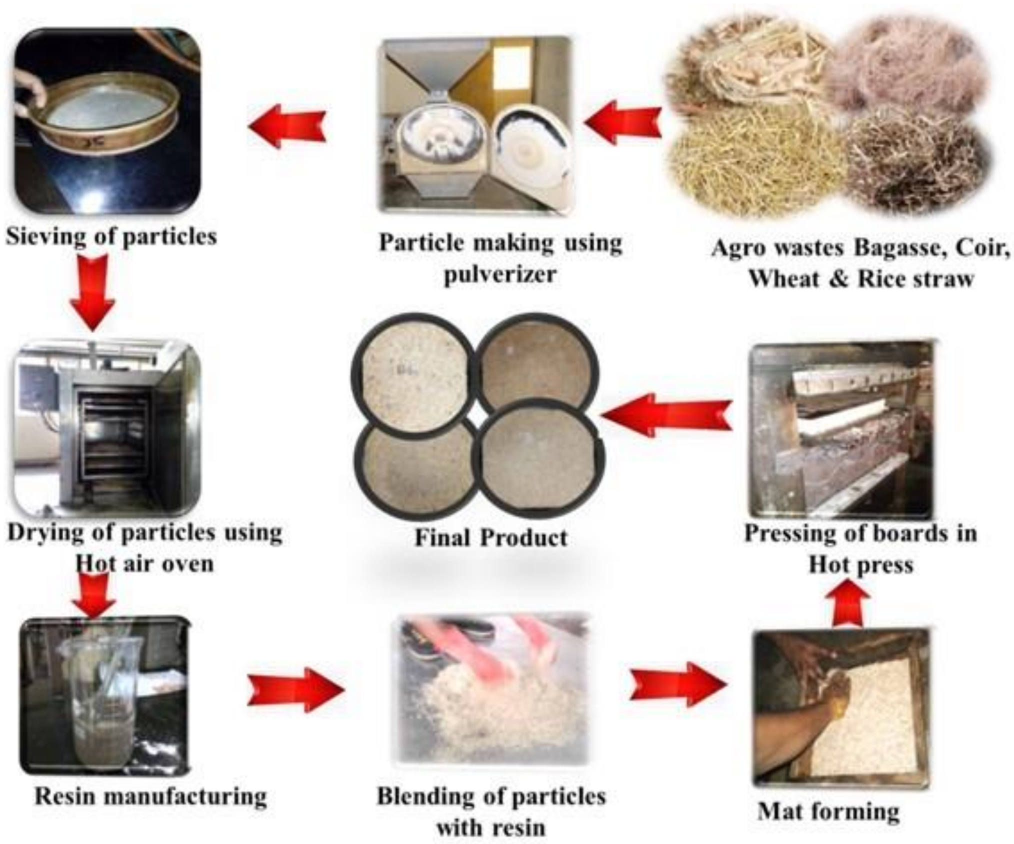

Fig. 1. Process cycle of manufacturing particle board from agro waste (bagasse, coir, rice straw, wheat straw)

The glue-coated particles in the form of a mat were subsequently placed into a hot press with dimensions of 350 mm × 350 mm. The platens temperature was kept within the range of 155 to 160 °C, and a specific pressure of 20 kg/cm^2 was applied during the compression cycle for 6minutes. Subsequently during the curing cycle, a specific pressure of 14 kg/cm^2 was maintained for a duration of 6 minutes. A total of 12 min pressing time was employed for 12-mm boards. Before being trimmed, the boards were left to stabilize for approximately 24 h at laboratory ambient conditions 25 °C and 65% RH to reach an equilibrium moisture content. Consequently, the trimmed boards were further dimensioned to meet the required sizes and subjected to testing in accordance with relevant specifications. All the boards using different agro residues were manufactured in the same process. Figure 1 illustrates the manufacturing process cycle of agro-residue boards, while Fig. 2 a, b, c, and d depict the pressed boards made from COIR, RS, BG, and WS, respectively.

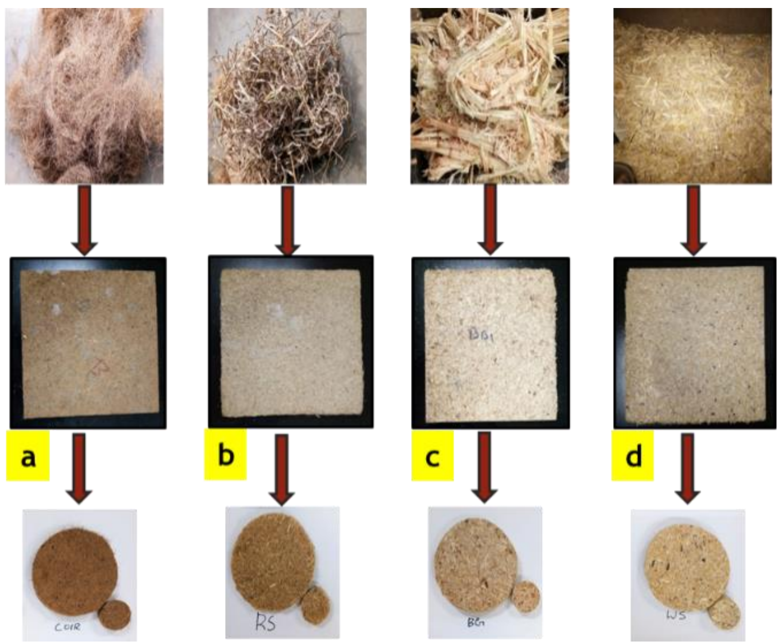

Fig. 2. (a) Coir board, (b) Rice straw board, (c) Bagasse board, and (d) wheat straw board

The manufacturing process details are provided in the flow chart in Fig. 1 and formulations of the boards are provided in Table 2. Particle boards were manufactured utilizing COIR, RS, BG and WS for each density such as 300, 400, and 500 kg/m³. The boards labelled RS were crafted from rice straw, BG from bagasse, WS from wheat straw and COIR for coir particles.

Table 2. Formulations of Boards

Sample name	RS3	BG3	WS3	COIR3	RS4	BG4	WS4	COIR4	RS5	BG5	WS5	COIR5
Targeted Density (kg/m^3)	300	300	300	300	400	400	400	400	500	500	500	500
Weight of particles (g)	340	340	340	340	500	500	500	500	630	630	630	630
Resin (g)	72	72	72	72	105	105	105	105	132	132	132	132

Testing and Characterization

Modulus of rupture, swelling, and water absorption

Test samples were exposed to ambient temperature and humidity levels of 27 °C and 65% RH respectively, to prevent variations in the results. The test samples remained in this controlled ambient condition until testing to ensure consistent results. Three replicates of samples were selected for each parameter. For the modulus of rupture (MOR), the dimensions of each specimen, including width, length and thickness, were measured with an accuracy of not less than ± 0.3%. The specimens were centrally loaded with a speed of loading 6 mm/min, and the testing was conducted following part 4 of IS 2380 (1977). Part 11 and 12 of IS 2380 (1977) were followed in the process of measuring water absorption and thickness swelling, respectively.

Sound absorption coefficient

For testing the SAC, an acoustic pulse tester was employed as per IS 10420 (1982). The device analyzes the incident and reflects components of random or pseudorandom noise generated inside the impedance tube by the sound source in order to determine the SAC. The acoustic features of the sample being tested have an impact on the reflected component. The specimen is positioned in a sample holder at one end of a straight tube and linked at the other end is a high-output acoustic driver that acts as a sound source. As shown in Fig. 3, a pair of microphones is flush with the cylindrical tube's inner wall close to the sample holder frame. Two microphones impedance tube were employed to determine the SAC of the test samples over a frequency range spanning from 50 to 5000 kHz (ASTM E1050-19 2019; IS 10420 1982; ISO 10534-2:2023; Koruk 2014).

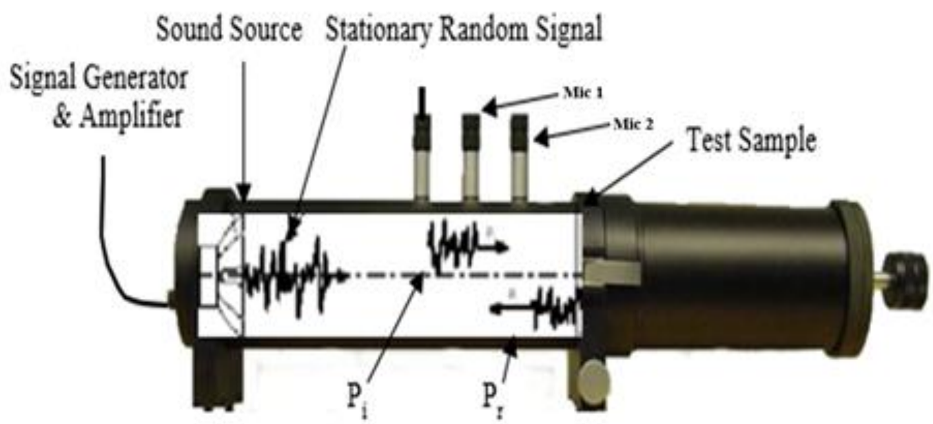

Fig. 3 Two micro-phone impedance tube used for measuring SAC

The SAC is described as the proportion of absorbed energy to the incoming energy. $\alpha = A_a/A_i$ (Astari et al. 2019; Shruthi and Kumar A 2020). Figure 4 illustrates the incident energy splitting into three different forms, namely reflected (A_r), absorbed (A_a), and transmitted (A_t).

Using the Acoustic Pulse Tester, three replicates of samples were prepared for the larger tube with a 100 mm diameter to assess the Sound Absorption Coefficient (SAC) in the frequency range of 50 to 1500 Hz. Three replicates of samples were prepared for the smaller tube with a 29 mm diameter to assess SAC in the frequency range of 1501 to 5000 Hz. SAC values were recorded for three densities: 300, 400, and 500 kg/m³. Additionally, the average SAC values at frequencies of 250, 500, 1000, and 2000 Hz were used to compute the Noise Reduction Coefficient (NRC).

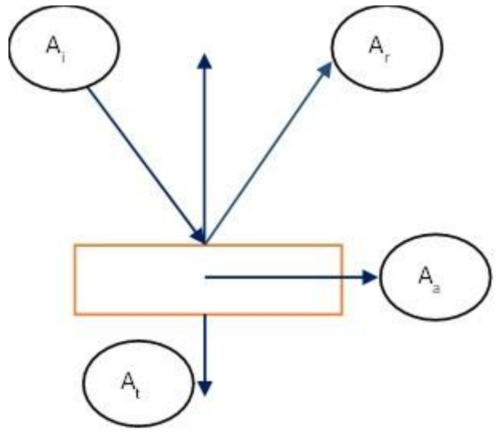

Fig. 4. Illustration of different sound energy

Thermal conductivity

The thermal conductivity of the samples was assessed following the procedure outlined in IS 3346:1980 (IS 3346:1980). This method is based on the guarded hot plate method and employs an absolute approach to determine thermal conductivity. The thermal conductivity apparatus consists of a guarded hot plate, primary guard plates, auxiliary cold plate, and cold plate. The primary guard plates, auxiliary cold plate, and guarded hot plate all must be kept at a higher temperature. Figure 5 illustrates the schematic layout of the guarded hot plate arrangement. The sample is heated to a varied temperature using both the cold plate and the guarded hot plate. To assess the thermal conductivity of the particle boards under consideration, the hot plate and cold plate have been set at 50 and 30 °C, respectively, on account of the harsh circumstances seen in all conditions.

Under steady-state circumstances, 100% of the energy from the guarded hot plate flows through the sample because the guarded hot plate, primary guard, and auxiliary cold plate are all at the same temperature. There is no upward heat transfer between the guarded hot plate and the auxiliary cold plate, nor is there any lateral heat exchange or flow between the guarded hot plate and the main guard. By tracking the voltage given to the heater and the current flowing through it, the quantity of energy passing through the guarded hot plate is calculated. Watts is the result of multiplying the voltage by the current. After that, the thermal conductivity of the sample is calculated using the metered energy in the guarded hot plate, considering the sample's thickness and the guarded hot plate's cross-sectional areas.

Equation 1 is used to calculate the thermal conductivity,

$$\mathrm{k} = \frac{HT}{St(\Delta K)}\text{, in W/m-K} \quad (1)$$

where H is heat supplied through the sample (W), S is cross-sectional area (m^2), ΔK is temperature differential across the sample (^{o}K), t is time in seconds, T is thickness of the sample through which heat flows (m), and k is thermal conductivity of the sample (W/m-K) (IS 3346 1980; Li and Ren 2011).

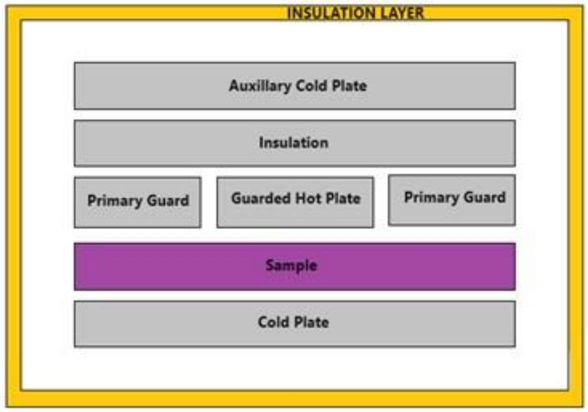

Fig. 5. Schematic diagram of guarded hot plate setup

For determining thermal conductivity, three replicates of samples with dimensions of 300 mm × 300 mm × 12 mm were produced for each of the three densities, namely 300, 400, and 500 kg/m³. Once a steady-state condition was established and there was a temperature difference of less than 0.5°C between the guarded metered hot plate and the main guard as well as the auxiliary cold plate, the thermal conductivity of the samples was calculated. Furthermore, this temperature differential was steady for four consecutive intervals, each lasting thirty minutes. Only after achieving a steady-state condition, readings were taken for the sample being tested. Statistical comparison using Two-way ANOVA between the sample values is summarized in Tables 4, 6, and 7.

RESULTS AND DISCUSSION

Chemical Analysis of Agro Residues

The analysis of agro residues RS, BG, WS, and COIR revealed significant differences in their chemical composition, particularly in terms of lignin, silica, and ash content. Lignin, a complex organic polymer, contributes to the structural integrity of the panels. From Table 3, the highest lignin percentage was found in COIR, while RS contained the least. Lignin also facilitated good interaction with formaldehyde-based adhesives, forming strong interfacial adhesion that enhances resistance to fracture. Silica content is essential for understanding the potential applications of these raw materials for the insulation. Its presence can reduce the bonding effectiveness with formaldehyde adhesives. In this study, the highest silica content 12.0% and 8.2% was found in RS and WS, respectively, while the lowest silica content 1.4% and 2.3% was found in COIR and BG, respectively.

Table 3. Chemical Analysis of the Agro Residues

Type of Agro Residue	Lignin (%)	Silica (%)	Ash (%)
RS	17.9	12.0	14.8
BG	21.7	2.3	2.9
WS	22.0	8.2	10.2
COIR	35.1	1.4	2.2

Modulus of Rupture (MOR)

The MOR findings suggest that the MOR values increased with an increase in density of the boards. From Fig. 6 and Table 4, the minimum MOR was found in 300 kg/m^3 particle boards. RS and WS boards with a density of 300 kg/m^3 had MOR values of 0.4 N/mm^2 and 0.9 N/mm^2 which is low indicating limited structural capacity. However, as the density increased to 400 kg/m^3, the MOR of RS and WS rose to 1.6 and 1.7 N/mm^2, respectively. Furthermore when density increased to 500 kg/m^3 it reached to 4.0 and 3.1 N/mm^2 respectively. This trend suggests that RS and WS are weak at lower density and can improve in strength with increased density. BG had higher MOR of 1.7 N/mm^2 for 300 kg/m^3. It reached 8.6 N/mm^2 at 500 kg/m^3. The higher strength of BG compared to RS and WS makes it more suitable for applications requiring greater structural strength. COIR exhibited the highest MOR values among all the tested agro residues boards, beginning at 2.5 N/mm^2 at 300 kg/m^3 and reaching an impressive 13.9 N/mm^2 at 500 kg/m^3. This exceptional strength of the COIR indicates that it is highly suitable for load-bearing applications, perhaps because the microfibrils are arranged helically at a 45° angle and also due to presence of more lignin content (35.1%) (Song 2017; Wang *et al*. 2024). The MOR of agro residue boards varied significantly with an increase in density ($p<0.05$). This expected finding is due to a higher material density, which implies less voids within the structure. The particles are effectively integrated into the board matrix, thus enhancing the overall structural integrity. This allows the board to withstand greater loads contributing to higher MOR values. A similar trend has also been observed in a homogeneous sugarcane bagasse board (Doost-Hoseini *et al.* 2014).

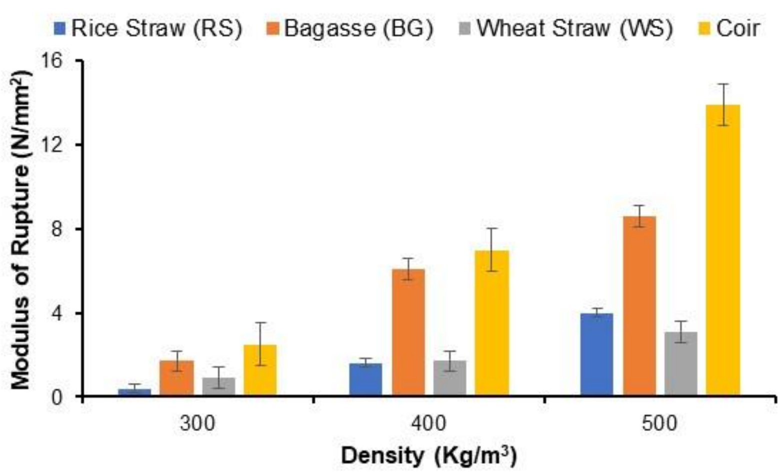

Fig. 6. Modulus of rupture of agro boards

Swelling due to Surface Absorption and Water Absorption

Figure 7 illustrates the swelling due to surface absorption. As the density increased from 300 to 500 kg/m^3, swelling due to surface absorption decreased proportionally, regardless of the type of agro-residue used. For instance, in WS the swelling values at densities of 300, 400, and 500 kg/m^3 were 6.9%, 4.7%, and 3.6%, respectively. Although, materials such as RS, BG, WS, and COIR all are lignocellulose in nature, the extent of swelling varied significantly ($p<0.05$) among these agro-residues.

Table 4. Agro-residue Particle Board's Mechanical and Physical Characteristics

SI No	Properties	Rice Straw			Bagasse			Wheat Straw			Coir		
		Density (kg/m^3)											
		300	400	500	300	400	500	300	400	500	300	400	500
1	Modulus of rupture (N/mm^2)	0.4 *	1.6*	4.0*	1.7*	6.1*	8.6*	0.9*	1.7*	3.1*	2.5*	7*	13.9*
		(0.04)	(0.04)	(0.07)	(0.08)	(0.12)	(0.04)	(0.04)	(0.08)	(0.06)	(0.17)	(0.25)	(0.14)
2	Thickness swelling due to surface absorption (%)	16.5*	14.2*	10.1*	4.9*	4.08*	2.4*	6.9*	4.7*	3.6	6.8*	4.8*	4.0*
		(0.59)	(0.58)	(0.61)	(0.23)	(0.15)	(0.23)	(0.55)	(0.10)	(0.08)	(0.12)	(0.08)	(0.14)
3	Water absorption	No disintegration and no splitting of boards along the edges and corners											

Note: values in parenthesis (standard deviation), * significant at 95%

Table 5. Sound Absorption Coefficient of Agro-residue Particle Boards in Comparison with Other Existing Acoustic Boards

Material Type	Density (kg/m^3)	Thickness (mm)	Max. SAC	References
RS	300	12	0.64	This study
BG			0.55	
WS			0.57	
Coir			0.8	
RS	400		0.39	
BG			0.48	
WS			0.51	
Coir			0.65	
RS	500		0.24	
BG			0.32	
WS			0.43	
Coir			0.55	
Mineral wool acoustic board	$\leq$ 500	9, 12, 15 and 19	0.4 to 0.6	(Li and Ren 2011)
Glass wool decorative ceiling board	48	15, 25	0.4 to 0.98	
Fiberglass wool acoustic board	50	10,18 and 20	0.7	
Hemp	50	30	0.2	(Berardi and Iannace 2015)
Coconut	60	100	0.75	
Cork	100	30	0.3	
Wood fibers	100	60	0.6	
Coir fiber panels	110	14	0.69	(Bhingare and Prakash 2020)
Granular polypropylene	500	10 to 50	0.20 to 0.421	(Sikora and Turkiewicz 2010)
Granular foamed polystyrene	1		0.24 to 0.34	
Granular gravelite	450		0.23 to 0.41	
Rubber granulate	460		0.25 to 0.52	
Mineral wool granulate	40		0.23 to 0.57	

A contributing factor may be their inherent chemical differences, as listed in Table 3. Thickness swelling of RS was quite high 16.5% for a density of 300 kg/m^3 and decreasing to 10.1% at 500 kg/m^3. These values indicate that the boards of RS were susceptible to moisture absorption, which would hinder its use in applications where exposure to water is a concern. BG boards showed significantly lower swelling percentages of 4.9% for 300 kg/m^3 and decreased to 2.4% for 500 kg/m^3. This minimum swelling suggests that BG is more resistant to moisture-related dimensional changes. WS exhibited 6.9% swelling at 300 kg/m^3, decreasing to 3.6% at 500 kg/m^3 better than RS indicating moderate moisture absorption at lower densities. COIR swelling started at 6.8% for 300 kg/m^3 and decreased to 4.0% at 500 kg/m^3, suggesting strong dimensional stability. Figure 7 indicates that BG, COIR, and WS offered good dimensional stability compared to RS. The swelling effect observed in RS is due to a weaker bond. The water-soluble MUF adhesive could not wet the straw surface due to the silica and wax on the outer surface, which resulted in a weak bond. Despite the higher values of swelling, the RS boards showed no splitting at the edges, no signs of disintegration and it remained intact in the water absorption test as mentioned in Table 4. In addition, all boards demonstrated excellent integration in the water absorption test, which can be attributed to effective bonding of particles, optimal process parameters such as particle size (2 to 3 mm for WS, RS, and COIR particles, and 1.5 to 3 mm for BG particles), optimal moisture content of particles before blending (3 to 4%), and appropriate pressing conditions (20 kg/cm^2 for the compression cycle and 14 kg/cm^2 for the curing cycle).

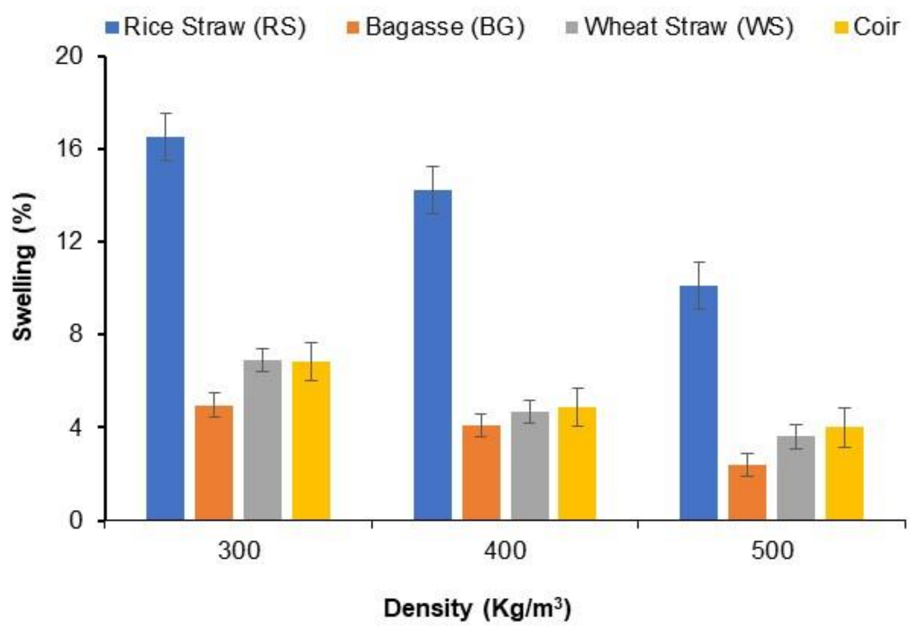

Fig. 7. Thickness swelling of agro-boards due to surface absorption values

Sound Absorption Coefficient

The SAC of boards with densities of 300, 400, and 500 kg/m^3 are presented in Figs. 8, 9 and 10 respectively. For all densities, COIR showed higher absorption at higher frequencies compared to lower frequencies while the other materials RS, BG, and WS demonstrated different absorption behaviors at different frequencies. For boards with density 300 kg/m^3, RS, BG, and WS exhibited the highest SACs of 0.64, 0.55, and 0.57 respectively, at 2000 Hz. In addition, the COIR exhibited a maximum SAC of 0.8 at 3000

Hz for 300 kg/m^3 (Fig. 8). At lower frequencies (125 to 250 Hz), the SAC values were generally low for all boards, regardless of density. Similar observations have been reported in bamboo boards made with two different densities and date palm fiber. The SAC values were similar for samples with same thickness but different densities at low frequencies (Al-Rahman *et al.* 2012; Karlinasari *et al.* 2012). An increase in density did not significantly improve sound absorption at lower frequencies. Denser materials (500 kg/m^3) at lower frequencies tended to show slightly lower absorption due to reduced porosity, which makes it harder for sound waves to penetrate and be dissipated.

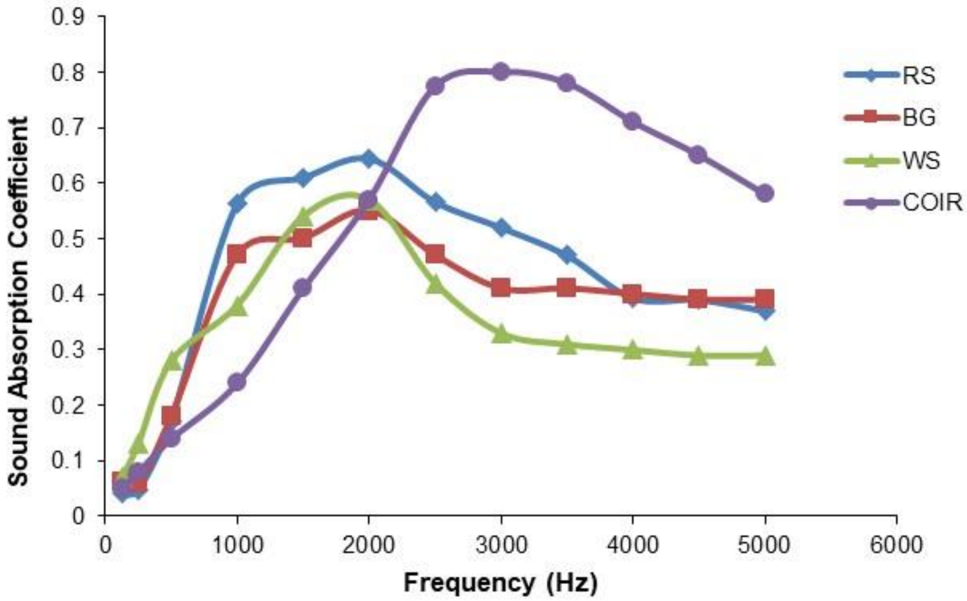

Fig. 8. Frequency vs. sound absorption coefficient of agro-residue particle boards of 300 kg/m^3

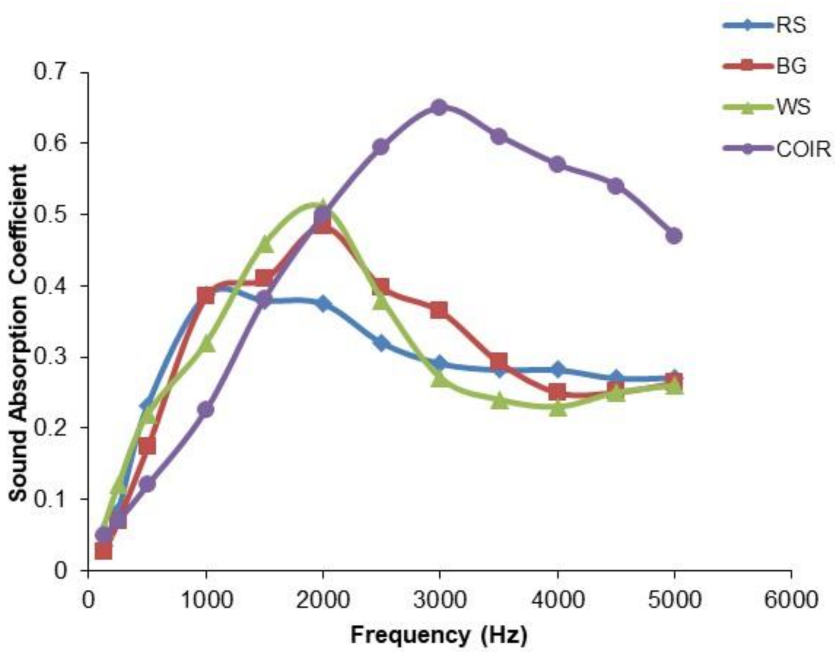

Fig. 9. Frequency vs. sound absorption coefficient of agro-residues particle boards of 400 kg/m^3

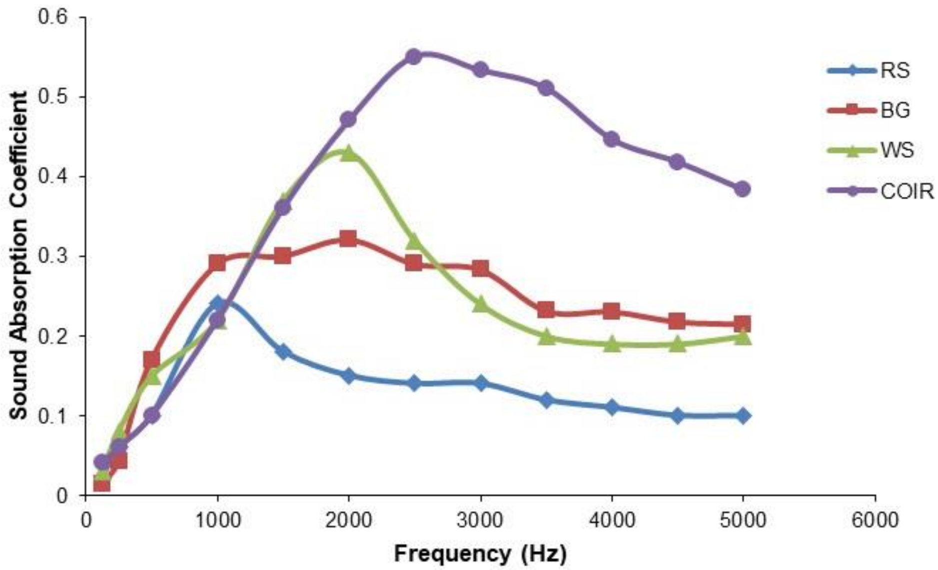

Fig. 10. Frequency vs. sound absorption coefficient of agro-residues particle boards of 500 kg/m^3

Boards of RS and WS started to show better performance, with SAC values peaking around 1000 to 2000 Hz. RS at 2000 Hz had an SAC of 0.64, BG had an SAC of 0.55, WS and COIR had SAC values of 0.57 for 300 kg/m^3. As density increased to 500 kg/m^3, SAC values of 0.15, 0.32, 0.43, and 0.47 were noticed for RS, BG, WS, and COIR, respectively for 2000Hz. The decreasing trend is most noticeable with RS, which showed a significant drop. COIR and WS were least affected, maintaining relatively high SAC at 2000 Hz even as density increased, which makes COIR and WS suitable for mid-range frequencies. At a frequency of 3000 Hz, RS, BG, WS, and COIR had SAC values of 0.52, 0.41, 0.33 and 0.80 respectively, for samples with a density of 300 kg/m^3. When the density increased to 400 kg/m^3 at the same frequency, the SAC values decreased to 0.29, 0.36, 0.27, and 0.65, respectively. With a further increase in density to 500 kg/m^3 the SAC values were observed to be 0.14, 0.28, 0.24, and 0.53 for RS, BG, WS, and COIR, respectively. Even at 3000 Hz, RS was the most affected by density increases, followed by BG and WS with moderate sensitivity. COIR showed the least sensitivity to density changes, maintaining strong absorption characteristics across different densities. Overall, RS at low density can be used for mid-frequency absorption but was significantly impacted by density changes, limiting its flexibility in application. The presence of more lignin content reduces pore size (Silviana *et al.* 2022), making the board more rigid and reducing the natural porosity, especially as density increases. The BG and WS offered balanced absorption performance and can serve as alternatives in cases where a balance between density and absorption is required. COIR is highly effective for high-frequency regions across all densities, making it the most adaptable material in this study.

Comparisons with other sound acoustic materials are listed in Table 5. When the average SAC across six frequencies (125, 250, 500, 1000, 2000, and 4000 Hz) exceeds 0.2, the material is classified as a sound-absorbing material. In this instance, all agro-residue boards with densities of 300 and 400 kg/m^3 showed SAC values greater than 0.2. Therefore, these agro- residues of 300 and 400 kg/m^3 fall into the category of sound-absorbing materials (Li and Ren 2011). Additionally, boards of all densities demonstrated promising sound absorption capabilities, achieving classifications of D and E under ISO 11654:1997, which can be attributed to their inherent material properties (ISO-11654-1997).

Noise Reduction Coefficient (NRC)

Acoustic panels are rated in terms of NRC, which represents the ability to reduce noise by the material. The NRC for the four agro-boards produced with a range of densities is shown in Table 6. Upon comparing the NRC of agro-residue boards across densities from 300 to 500 kg/m³ in ascending order, it is observed that RS boards showed a 64% reduction, indicating the biggest difference, followed by BG boards with a reduction of 37%. WS exhibited a 34% reduction in NRC. However, for COIR, the NRC showed a negligible level of decrease, while other boards experienced a drastic reduction in NRC with increasing density. The statistical analysis revealed the significant difference with respect to increase density and variation in agro residues ($p<0.05$). Figure 11 clearly illustrates that the Noise Reduction Coefficient (NRC) decreased as board density increased. The trend lines and the R^2 values (coefficient of determination) for all four agro-residue boards are also shown in the Fig. 11, highlighting the strength of the correlation between density and sound absorption performance.

Table 6. NRC of Agro-residues Particle Boards

Sample and Density in kg/m³	300				400				500			
	RS	BG	WS	COIR	RS	BG	WS	COIR	RS	BG	WS	COIR
NRC	0.41* (0.01)	0.35* (0.02)	0.38* (0.01)	0.29* (0.02)	0.29* (0.02)	0.3* (0.01)	0.33* (0.02)	0.26* (0.01)	0.15* (0.01)	0.22* (0.01)	0.25* (0.0.03)	0.24* (0.0.03)

Note: values in parenthesis (standard deviation), * significant at 95%

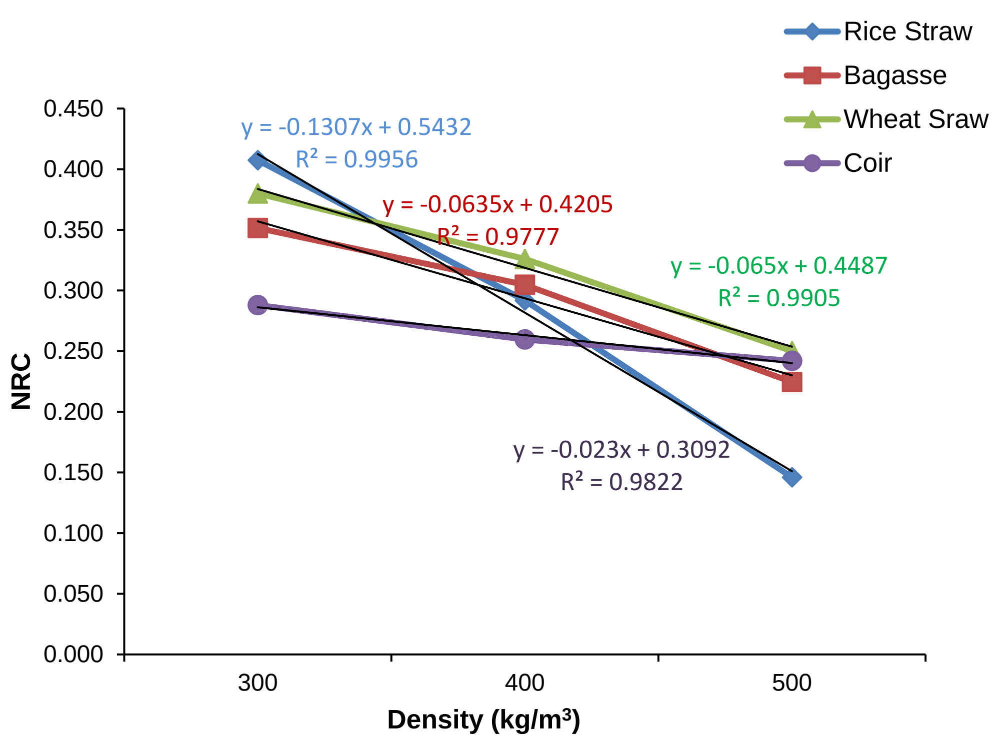

Fig. 11. NRC vs. density of agro-residues particle boards

The NRC of RS boards exhibited a swift decline with escalating density. Silica particles in RS can help scatter sound waves, particularly at lower densities, which contributed to better sound absorption. However, increasing the density of RS boards due to higher silica content made them harder, causing more sound waves to be reflected. This is directly linked to a decrease in the Noise Reduction Coefficient (NRC). The linear trend line equation was given by $y = -0.1307x + 0.5432$, with a coefficient of determination of $R^2 = 0.9956$. The NRC results for the 300 and 400 kg/m³ boards demonstrated comparable performance to wadding material, insulation fiberboard, and boards made from wood wool (Nandanwar *et al.* 2017).

Thermal Conductivity

The average thermal conductivity values of agro-residue boards RS, BG, WS, and COIR and their statistical comparison in relation to density are presented in Table 7 and Fig. 12. The results illustrate that thermal conductivity (*K*) increased with increasing density across all agro-residue boards. This is because denser materials have fewer air pockets, allowing for greater heat transfer. The reduction in air content, which is a poor conductor of heat, enables heat to pass more easily through the solid structure of the materials (Stacy *et al.* 2014). The results indicate a significant variation in thermal conductivity with respect to density ($p < 0.05$), but no significant differences among the agro residues themselves ($p > 0.05$), suggesting that some residues behave similarly across different density levels. BG consistently showed the highest thermal conductivity across all densities (0.121 to 0.177 W/m-K). This suggests that BG compared to the other materials, facilitated heat transfer more effectively due to its inherent structure and composition. RS and WS showed similar thermal conductivity values at lower densities, but as density increased, WS thermal conductivity rose more quickly than RS. This indicates that WS became more conductive as it got denser. RS with 12% silica and WS with 8.2% silica content contributed to reduced heat transfer with improved thermal stability (Hussein *et al.* 2019; Silviana *et al.* 2022). COIR showed thermal conductivity values ranging from 0.120 to 0.169 W/m-K.

For a board intended to be used for thermal application, apart from the density, the material's inherent characteristics also play a vital role. In practical design situations where heat insulation is being measured, it seems feasible to estimate thermal conductivity from density using the suggested design curves presented for each kind of agro-residue particle boards. Overall, RS and WS were judged to be more suitable for low-thermal conductivity applications, whereas COIR and BG were better suited for moderate thermal applications.

Table 7. Thermal Conductivity of Agro-residues Particle Boards Compared with Other Agro Particle Board

SI No	Sample	Density (kg/m³)	Thermal Conductivity (W/m-K)		
			300	400	500
1	Rice Straw	Avg	0.098*	0.119*	0.133*
		STD Dev	(0.004)	(0.002)	(0.004)
2	Bagasse	Avg	0.121^{ns}	0.157^{ns}	0.177^{ns}
		STD Dev	(0.004)	(0.003)	(0.003)
3	Wheat Straw	Avg	0.099^{ns}	0.127*	0.152*
		STD Dev	(0.004)	(0.005)	(0.012)
4	Coir	Avg	0.120*	0.138^{ns}	0.169^{ns}
		STD Dev	(0.006)	(0.004)	(0.005)

Note: values in parenthesis (standard deviation), * significant at 95%, ^{ns} non-significant at 95%

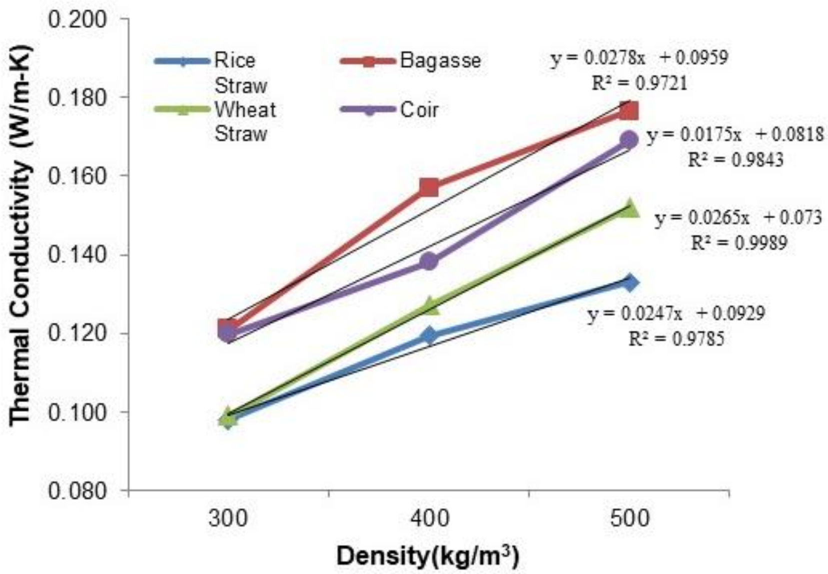

Fig. 12. Density vs. thermal conductivity of agro-residues particle boards

CONCLUSIONS

This study explored the significance of density on the physical, mechanical, acoustics and thermal properties of particle boards manufactured from rice straw (RS), bagasse (BG), wheat straw (WS), and COIR. The results indicate that agro residues can be a suitable substitute raw material for particle board manufacturing for acoustic and thermal applications.

1. The density of particle boards and the type of agro-residues used as raw materials (RS, BG, WS, and COIR) are the main factors influencing their physical and mechanical properties. Increasing the density from 300 to 500 kg/m³ enhanced the modulus of rupture (MOR) and reduced thickness swelling. Conversely, particle boards exhibited better sound absorption coefficient (SAC), noise reduction coefficient (NRC), and thermal conductivity when density decreased. These effects are attributed to the inherent chemical compositions of the agro-residues

2. The high lignin content in coir contributes to a superior modulus of rupture (MOR), resulting in greater overall mechanical stability compared to other agro-residues. RS, with its high silica content, scatters sound waves and dissipates energy more effectively at lower densities, leading to improved SAC at 2000 Hz compared to other agro boards. However, as density increases, the high silica content makes the board more rigid, causing sound waves to reflect, which significantly reduces the SAC.

3. The maximum peak sound absorption coefficient (SAC) for RS, BG, and WS boards was found at a frequency of 2000 Hz, while for the coir board, the maximum SAC was observed at 3000 Hz. Coir boards were judged to be more suitable for high-frequency regions, whereas RS, BG, and WS boards can be preferred for applications in lower frequency regions. These findings suggest that particle board made from agro-residues can be used in applications such as theaters and auditoriums, office spaces, music rooms,

sound recording studios, commercial and residential buildings, including prefabricated modular homes.

4. RS can be highly effective, particularly at mid frequencies, with an NRC of 0.41 at 300 kg/m^3. This positions RS as a strong candidate for applications focused on noise control. However, its NRC was found to be severely impacted by density and due to its high swelling characteristics, it is recommended for use in modular acoustic panels that can be easily replaced or repaired if swelling occurs. This allows for flexibility in design while ensuring that acoustic properties are maintained.
5. Based on thermal conductivity findings, RS and WS are recommended for applications focused on thermal insulation due to their lower thermal conductivity. The presence of silica enhances thermal resistance because of its low thermal conductivity. Meanwhile, BG and COIR, despite their higher thermal conductivity, are suitable for applications that require a balance between heat transfer and sound control.
6. Further investigation into the long-term durability, porosity, microstructure, varying thickness with different resin system and ratios of these materials will enhance their applicability. Exploring hybrid materials or composites could lead to improved performance characteristics and broaden their use in various applications.

The overall findings can inform architects and builders in their material selection processes, enabling the creation of spaces that are both comfortable and sustainable. The ability to optimize specific acoustic and thermal requirements will enhance the functionality of living and working environments.

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Conflict of Interest

The authors declare no conflict of interest.

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