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Evaluation of physical and acoustic properties of composite boards from sugarcane bagasse and oil palm empty fruit bunch waste

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Abstract

Bagasse and empty fruit bunches of oil palm are abundant waste products in Indonesia's plantation industry, posing environmental challenges if not managed effectively. However, these waste materials can have harmful environmental effects. One approach to mitigate this impact is to use them as composite materials. This approach aligns with the growing emphasis on environmental sustainability. This study examined the impact of incorporating epoxy resin into Polyvinyl Acetate (PVAc) adhesives on acoustic board composites made from sugarcane bagasse waste reinforced with empty palm fruit bunch fibers. Hybrid fibers from bagasse (67%) and empty palm fruit bunches (3%) were combined with an epoxy resin-PVAc adhesive matrix (30%) with epoxy resin-to-PVAc ratios of 0:30, 1:29, 2:28, and 4:26%. The boards were manufactured using the cold press method (20 MPa, 30 min) and air-dried for 7 days. The results indicate that increasing the epoxy resin content enhances both the physical and acoustic properties, with Sound Absorption Coefficients (SACs) of 0.37, 0.42, 0.40, and 0.67 for 0%, 1%, 2%, and 4% epoxy resin, respectively. This study highlights the feasibility of utilizing agricultural waste for sustainable engineering applications, thereby contributing to the development of eco-friendly materials.

Keywords:
Waste, sugarcane bagasse, empty palm fruit bunches, physical properties, and acoustics

1 Introduction

Noise and vibration are significant issues in various mechanical systems, including industrial machines, household appliances, vehicles, and buildings. These disturbances can negatively affect environmental comfort, making it essential to reduce them. The use of noise-absorbing materials is crucial to mitigate these effects.

Currently, most sound-absorbing or sound-dampening materials available in the market are synthetic. Synthetic materials used as acoustic boards include glass wool, foam glass, mineral wool, and polyester fibers. These materials effectively absorb sound; however, they harm human health and the environment by contributing to pollution and global warming [1, 2]. These conditions affect the sustainability of nature. As a result, research on using natural acoustic panels is now trending.

In 2023, sugar production was projected to reach 2.23 million tons [3]. The processing of one ton of sugarcane stalks produces approximately 0.25 to 0.30 tons of bagasse [4]. Unfortunately, this by-product has not been optimally utilized. Waste generated from sugar and Palm Oil (PO) production in Indonesia continues to increase with the rising consumption of sugar and oil.

Natural fibers provide a comfortable environment by reducing noise levels, enhancing organic design, and minimizing potential health issues. Various studies have explored the potential uses of bagasse waste, including applications in biomass energy [5], particleboard [6], hybrid bio-panels [7], binder-less board [8], lightweight engineered wood [9], porous absorber [10], inorganic binders [11], and in mortar and concrete [12-18].

Organic waste, which is abundant in Indonesia, includes PO. In 2023, Crude Palm Oil (CPO) production reached 47.08 million tons, with a land area of 19.93 million hectares [15]. Nearly all parts of the palm tree can be utilized as engineering materials, including Oil Palm Fronds (OPFs), Oil Palm Trunks (OPTs), and Empty Fruit Bunch (EFB) particles. Composites made from OPT and OPF particles exhibit better mechanical strength and dimensional stability than those made from EFB [16].

PO fibers can enhance various properties of composites, such as porosity, density, stress, and deflection; however, they may reduce the elastic modulus [17]. The density and size of Oil Palm Frond (OPF) particles used as reinforcement in particleboards significantly influence their sound absorption performance. Composites incorporating OPF fibers exhibit high sound absorption capabilities [18]. These composites showed greater sound absorption values (α_n) for medium and coarse particle sizes, with a value of $\alpha_n = 0.95$. Furthermore, composites reinforced with OPF fibers are effective sound insulators across a wide frequency range, particularly for absorbing medium-to high-frequency sounds.

The accuracy of the fiber content and panel thickness is are crucial factors that affect the sound absorption performance of acoustic boards. Panels with thicknesses of 40 mm and 50 mm and a density of 0.292 g/cm^3 achieved a Sound Absorption Coefficient (SAC) of 0.9 in the frequency range above 1 kHz. However, the sound absorption rate tended to decrease as the thickness of the composite material increased. This increase in thickness also resulted in a higher number of fibers in the sample, which reduced its porosity [19]. An air cavity can be created behind the panel to enhance acoustic performance at low frequencies. Notably, the acoustic performance of panels made with Oil Palm Empty Fruit Bunch (OPEFB) fibers is comparable to that of panels made with synthetic rock wool fibers [20]. The selection of sugarcane bagasse and empty oil palm fruit bunch fibers as acoustic boards is based on their abundance, low cost, and reasonably effective performance.

The matrix in a composite material plays a crucial role as it binds all the components that make up the composite. The types of matrices used in acoustic boards include epoxy resin, Polypropylene (PP), Polylactic Acid (PLA), Polyurethane (PU), PU-polyurethane, PP-polyurethane, polyester, PU-Thermoplastic Polyurethane (TPU), Polyethylene Terephthalate (PET), natural rubber, phenolic resin, urea-formaldehyde, and melamine-urea-formaldehyde [21]. The incorporation of Polyvinyl Chloride (PVC) into epoxy resin can enhance its plasticization, indicating that PVC serves as a plasticizing agent for epoxy [22]. The addition of PVAc led to a 2.4-fold increase in the fracture toughness compared to that of pure epoxy resin [23].

Mawardi et al. [9] created environmentally friendly and sustainable thermal insulation materials using a mixed matrix of tapioca starch and Polyvinyl Acetate (PVAc) in an 80:20 ratio. They found that as the content of the matrix decreased, both the thermal stability and resistance improved, although this also led to a reduction in density.

Epoxy resin is known for its high mechanical strength, whereas PVAc offers flexibility and good bonding properties. The combination of these adhesives is expected to optimize the acoustic and physical performance of the composite. By evaluating the acoustic behavior of these hybrid composite boards using impedance tube measurements, this study provides new insights into sustainable sound-absorbing materials with potential applications in architectural acoustics, automotive soundproofing, and industrial noise control.

Previous studies have investigated the diversity of natural fibers, fiber content, board thickness, and design of acoustic boards. However, research on the engineering of PVAc adhesives modified with epoxy resin and their effects on acoustic properties remains limited. Considering this gap, the current study aims to investigate how varying the epoxy resin content in PVAc adhesives influences the physical and acoustic properties of acoustic boards made from sugarcane bagasse waste and reinforced with OPEFB fibers.

2 Method

2.1 Materials

Fig. 1 illustrates the raw materials for acoustic boards: waste from sugarcane bagasse and fibers from empty oil palm bunches. The EFB fibers used in this study were sourced from Rangkasbitung. The base of each bunch was cut off, and the fibers were extracted. The fiber extraction process begins by crushing the EFB in a crusher, followed by manual fiber separation. After drying and cleaning, the EFB fibers were processed using a ball mill. The fiber was then cut into pieces measuring 20 mm in length. The density of EFB fiber ranges from 0.42 to 0.53 g/cm³. The tensile strength of EFB fiber is between 19.02 and 21.28 MPa, while the modulus of elasticity is 928.98-1538.17 MPa. The composition of the EFB fibers included cellulose (45.95%), hemicellulose (22.84%), lignin (16.49%), ash (1.23%), nitrogen (0.53%), and oil (2.41%).

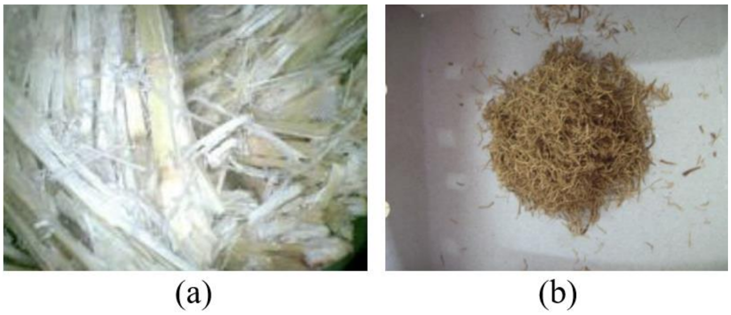

Fig. 1. Organic materials for acoustic board: (a) sugarcane bagasse, and (b) EFB fiber

Sugarcane bagasse waste is sourced from a local industry that sells sugarcane juice drinks in the Cilegon - Banten area. The bagasse collected was dry, white in color, and contained fine pulp fibers. Before use, the sugarcane bagasse was soaked in plain water for three days to remove the sugar content from the stalks. After soaking, bagasse was crushed or chopped to achieve the desired mesh size during ball milling. Subsequently, the sugarcane bagasse was sifted to obtain an 18-mesh size. The coarse size of bagasse results in a low density [8, 24], which increases the SAC [25]. Sugarcane bagasse consists of cellulose (45-55%), lignin (20-34%), hemicellulose (20-34%), and other extractive substances (2-6%) [26]. Its density is 1.2 g/cm³, tensile strength ranges from 20 to 290 MPa, Young's modulus is 19.7-27.1 GPa, and elongation at break is 1.1% [27].

The PVAc adhesive used as a matrix was a commercially available product under the brand name Fox Glue. This glue was selected for its environmentally friendly properties, low cost, and ease of use [28]. The specifications of the PVAc glue are as follows: it appears as a paste with a milky white color, has a viscosity of 250000-400000 cps at 30°C, a density ranging from 0.94 to 0.96 kg/L at 30°C, and a solids content of 28-30%.

Epoxy resin serves as the matrix in a hybrid with PVAc, featuring the following properties: density of 1.15 g/cm³, tensile shear adhesion of 148 kg/cm², compressive strength of 1034 kg/cm², flexural strength of 912 kg/cm², and hardness Rockwell R of 85.

2.2 Pre-treatment of fillers and fibers

The fibers from empty oil palm bunches and sugarcane bagasse were subjected to alkali treatment by soaking them in a 5% NaOH solution for 5 min. This initial treatment altered the surface morphology of the fibers and removed the waxy layer. A previous study indicated that a 5% alkali treatment for 5 min effectively removed most lignin and hemicellulose [29]. After alkali treatment, the fibers were washed thoroughly with distilled water until a pH of 7 was reached. Finally, the fibers were dried in the sunlight for three days.

2.3 Manufacturing acoustic board composites

The composition of the natural fiber-based acoustic boards was organized according to the volume fractions, as presented in Table 1. The typical fiber-to-matrix ratio was 70:30. Chougala et al. [30] investigated fiber and matrix ratios of 60:40, 70:30, and 80:20. These findings indicated that as the bagasse fiber content increased, the density decreased. Additionally, sound-absorbing composites made from bagasse, with a composition of 80% bagasse fiber and 20% PVAc, exhibit varying densities based on different thicknesses and weights. The high-density panel achieved an acoustic SAC of 0.98 at mid-frequency [31].

Table 1. Composition of the acoustic board based on the volume fraction

Sample	Bagasse (vol.%)	OPEFB (vol.%)	Epoxy resin (vol.%)	PVAc adhesive (vol.%)
ER0	67	3	0	30
ER1	67	3	1	29
ER2	67	3	2	28
ER4	67	3	4	26
CPB (Commercial Particle Board)				

Sugarcane bagasse particles were mixed with empty oil palm bunch fibers using an electric mixer for 15 min at 700 rpm. Next, the epoxy resin, hardener, and PVAc adhesive were added to the mixture and stirred for an additional 15 min. The mixture of raw materials was allowed to rest for 30 min to enhance its viscosity, thereby minimizing material leakage during the compaction process.

The composite mixture was then placed in a mold with a diameter of 100 mm. Compaction was performed using the single-punch cold-press method by applying a pressure of 2 MPa for 30 min. After compaction, the sample was released from the mold and left to dry in the sun for 7 days.

2.4 Acoustic test equipment setup

Fig. 2 illustrates the setup of the acoustic test equipment. Before using the device, it was calibrated. First, the signal-to-noise ratio (S/N ratio) was adjusted to ensure that the signal in the impedance tube was at least 10 dB greater than ambient noise. Next, the transfer function was calibrated by placing the absorptive specimen and measuring the transfer function at both the initial microphone position and the exchanged position.

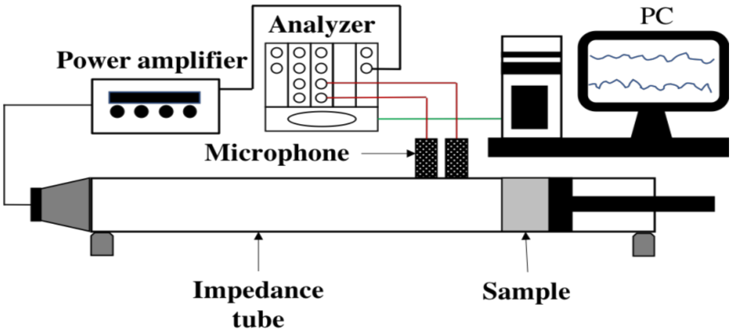

Fig. 2. Equipment setup

2.5 Material characterization

Density. Density is one of the parameters that determines the properties of a composite. The density was measured at room temperature according to the ASTM D1895 standard using Eq. (1). Density testing involves weighing a composite sample and measuring its volume to determine its density [32].

$$\rho = \frac{m}{\upsilon} \tag{1}$$

where ρ is the density (g/cm³), m is the mass of the composite (g), and υ is the volume of the composite (cm³).

Porosity. Porosity refers to the amount of void space compared with the total geometric volume of the composite material. It plays a crucial role in the diffusion of fluid molecules. Porosity is a significant concern in the manufacturing of composites. This occurs when air or volatile gases are trapped during the curing process. The porosity of the composite was calculated using Eq. (2).

$$n = 1 - \frac{\rho}{\rho_{th}} \tag{2}$$

where ρ is the actual density (g/cm³) and ρ_{th} is the theoretical density. The theoretical density can be calculated using Eq. (3) with the rule of mixtures.

$$\rho_{th} = \sum_{i=1}^{n} \rho_i \upsilon_i \tag{3}$$

where ρ_i is the density of the *i-th* constituent, υ_i is the volume fraction of the *i-th* constituent.

Sound absorption tests were performed using the Bruel and Kjaer type 4206 impedance tube method to assess the acoustic properties of the soundproofing composites. A two-microphone impedance tube was used as the testing apparatus following the ASTM E 1050-98 standard. The goal of the absorption test is to assess the ability of a material to absorb sound. A round specimen with a diameter of 100 mm and a thickness of 20 mm was placed at the end of the impedance tube. The sound frequency was then set on the amplifier, ranging from 100 to 1600 Hz.

The surface morphology was analyzed using an Olympus™ Optical Co. Ltd BX41 optical microscope. Cross-sectional morphology analysis was performed to investigate the distribution of voids and constituents of the composite.

3 Results and discussion

3.1 Density

The density is a crucial physical property of composite boards that significantly affects other mechanical properties. According to the testing results, the density of the composite boards ranges from 0.44 g/cm³ to 0.67 g/cm³. This range indicates that the composite boards produced meet the specifications outlined in JIS A 5908-1994.

Fig. 3 demonstrates a positive correlation between the epoxy resin content and composite density, confirming that the epoxy resin acts as a densifying agent owing to its inherently high density. This was attributed to the high density of epoxy resin. Therefore, increasing the volume fraction of epoxy resin in the composite led to a higher density of the resulting material. This phenomenon aligns with the findings of various studies conducted by other researchers [33, 34, 35].

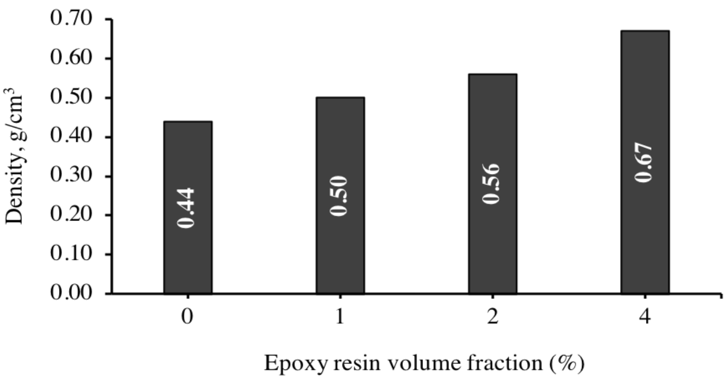

Fig. 3. Relationship between the epoxy resin content and composite density

When the epoxy resin cures in the mixture with PVAc, it acts as a filler and can influence the mechanical properties of the composite. A concentration of 4 wt% provides the optimal homogeneous dispersion and interfacial interaction [36-38]. An increase in the amount of epoxy resin resulted in a higher density of the polymer composite. According to the rule of mixtures, this increase in composite density is attributed to the higher density of epoxy resin compared to that of PVAc.

3.2 Porosity

Porosity and density are critical factors in determining the acoustic properties of composites. The degree of porosity significantly influences the acoustic behavior of the material. The SAC can be adjusted by varying the quantity and density of the adhesive used [39]. As shown in Fig. 4, an increase in the epoxy resin content of the acoustic board corresponded to a decrease in porosity. This indicates that porosity is inversely proportional to the density of the acoustic board [40].

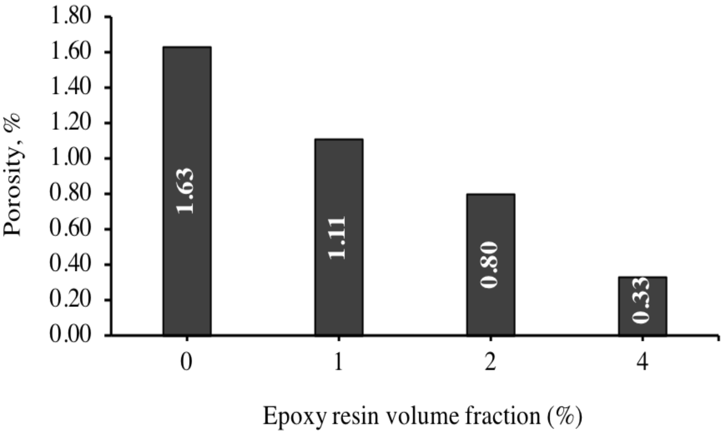

Fig. 4. Relationship between the epoxy resin content and composite porosity

Fig. 5 presents an optical microscope image showing the distribution of materials in the acoustic board composite. Epoxy resin is represented in yellow, bagasse in blue, EFB fiber in green, and PVAc adhesive in white. Notably, the ER0 sample displays the highest level of porosity (Fig. 5(a)). In contrast, an increased presence of epoxy resin appears to decrease the porosity of the acoustic board composite.

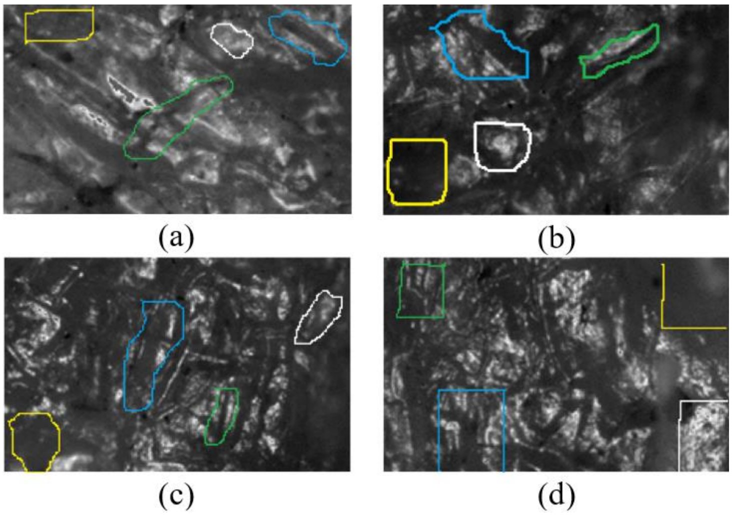

Fig. 5. Surface morphologies of acoustic board composites with varying epoxy resin contents: (a) 0%, (b) 1%, (c) 2%, and (d) 4%

3.3 Sound Absorption Coefficient

Fig. 6 demonstrates that the SAC significantly increases in acoustic boards containing 4% epoxy resin within the 1000-1300 Hz frequency range. The study indicates that sound absorption improves within this specific frequency range, suggesting that a higher epoxy resin content is associated with enhanced sound absorption at elevated frequencies. Samples with 1% epoxy resin exhibited the highest absorption coefficient at 820 Hz, while those with 2% and 4% epoxy resin recorded peak absorption coefficients at 1192 Hz and 1222 Hz, respectively.

Additionally, the presence of epoxy resin in the hybrid with PVAc within the composite board markedly influenced the sound absorption coefficient. These results align with the findings of a study conducted by Kalauni and Pawar [41], which indicated that using the Grewia Optiva fiber in hybrid composites of epoxy resin and pine matrix outperformed pure epoxy resin composites.

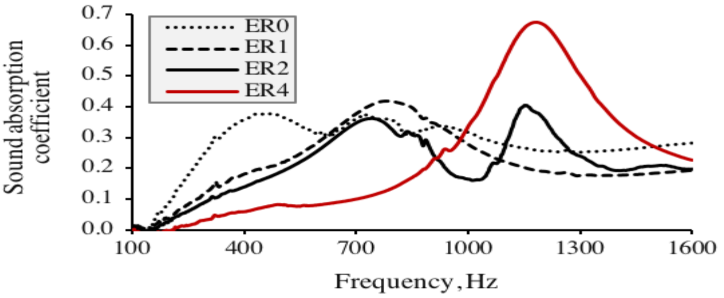

Fig. 6. The SAC spectrum of acoustic boards featuring different epoxy resin contents

All the samples showed a decrease in the SAC after reaching their peak values. This decline can be attributed to energy loss in the form of heat owing to inelastic collisions. The decline in SAC at higher frequencies may result from the coincidence dip phenomenon, where incoming and reflected waves are in phase, reducing the absorption [41].

Fig. 6 shows that sugarcane bagasse waste and empty oil palm bunch fibers demonstrate a competitive acoustic performance compared to commercially available acoustic boards. Haryono et al. [42] found that using sugarcane bagasse combined with a PVAc matrix yields a noise absorption coefficient ranging from 0.46 to 0.71 at frequencies between 400 and 800 Hz. Additionally, other studies support this finding, indicating that a decrease in the amount of PVAc or urea-formaldehyde in the matrix tends to reduce the absorption coefficient [39].

Fig. 7 illustrates the SAC of acoustic board composites made with a PVAc matrix and no additional epoxy resin. The SAC values of these acoustic board composites (ER0) were higher than those of commercially available acoustic boards. The highest SAC value recorded was 0.44, which occurred at a frequency of 444 Hz.

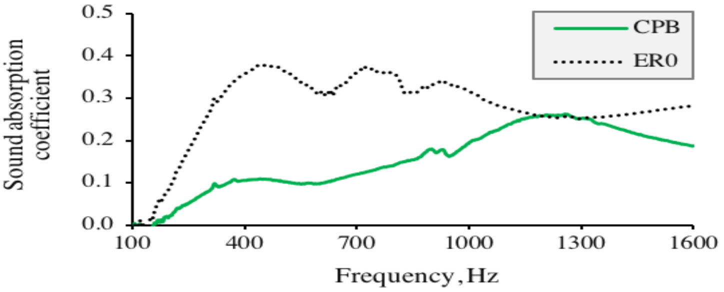

Fig. 7. Comparison of SAC values between composite boards without epoxy resin and commercial acoustic boards

Fig. 8 compares the SAC of composite boards without epoxy resin with that of commercial boards. The SAC reaches its highest value of 0.50 at a frequency of 788 Hz.Within the frequency range of 150–1100 Hz, the developed composite board exhibits better SAC performance than certain brands of acoustic boards available on the market. The commercial acoustic board referenced in this study has a SAC of 0.26 within the frequency range of 950 to 1600 Hz. This improvement was attributed to the resonance properties of the composite material. However, there is a noticeable decline in the SAC between 1100 and 1600 Hz, indicating that the material is less effective at absorbing sound at higher frequencies.

The findings of this study are consistent with those of Song et al. [43], which indicated that the number of pores influences the SAC across various specimens. The decrease in the SAC value after the initial peak is attributed to the reduced pore connectivity at higher frequencies, which makes the sound absorption less effective.

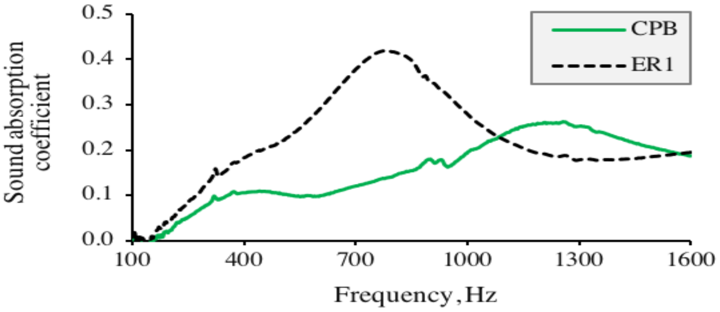

Fig. 8. Comparison of SAC values between composite boards with 1% epoxy resin and commercial acoustic boards

The addition of 2% epoxy resin produced a unique pattern compared with the other acoustic board samples. At a frequency of 1150 Hz, this configuration had a SAC of 0.40, as illustrated in Fig. 9. The inclusion of 2% epoxy resin significantly enhances the resonance effect. Shen et al. [44] demonstrated that the perforation rate affects the sound absorption performance of nanofiber membranes. In particular, the sound absorption value increased as the perforation rate increased.

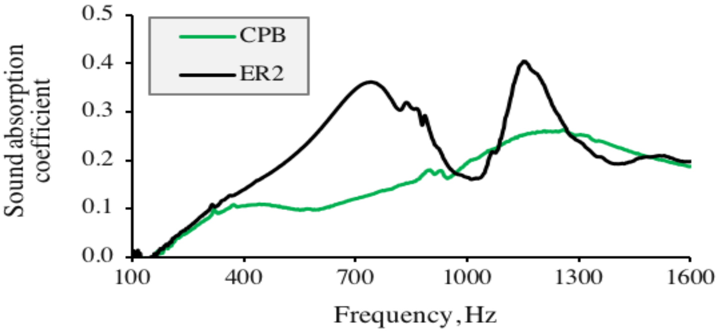

Fig. 9. Comparison of SAC values between composite boards with 2% epoxy resin and commercial acoustic boards

The composite board with 4% epoxy resin exhibited the highest SAC, indicating optimal sound absorption properties compared with the other acoustic boards. Its ability to absorb sound effectively is highlighted by the broad sound absorption spectrum observed in the range–950-1600 Hz, indicating good porosity.

Fig. 10 compares the SAC of an acoustic board with 4% epoxy resin content to that of an acoustic board currently available on the market. The composite board with 4% epoxy resin exhibited the highest SAC, indicating optimal sound absorption properties compared with the other acoustic boards. Its ability to absorb sound effectively is highlighted by the broad sound absorption spectrum observed in the range–950-1600 Hz, indicating good porosity.

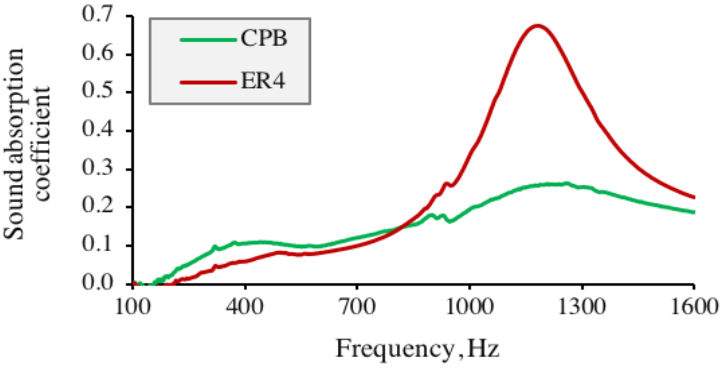

Fig. 10. Comparison of SAC values between composite boards with 4% epoxy resin and commercial acoustic boards

4 Conclusions

Acoustic boards were successfully produced from sugarcane bagasse and oil palm empty fruit bunch (EFB) fibers, bonded with a hybrid matrix of PVAc adhesive and epoxy resin. Based on the data and analysis of the test results, the following conclusions can be drawn:

First, increasing epoxy resin content significantly improved the physical properties and sound absorption performance of the boards. All samples satisfied the ISO 11654 standard ($\alpha > 0.15$), qualifying as effective sound-absorbing materials. Second, Performance results showed that the board with 4% epoxy resin (ER4) achieved the highest sound absorption coefficient of 0.67 across the 950–1600 Hz frequency range. ER4 also demonstrated the highest density (0.67 g/cm³) and the lowest porosity (0.33%), suggesting a positive relationship between reduced porosity and improved acoustic performance in mid-to-high frequencies. Third, Comparison analysis confirmed that the ER4 sample outperformed commercial acoustic boards, which typically exhibit a sound absorption coefficient of around 0.26 within the same frequency range, showing the high potential of waste-based materials. Fourth, contributing to environmental sustainability, this research highlights the feasibility of converting agricultural waste into high-performance, eco-friendly acoustic materials.

Future research should explore the effects of fiber pretreatment, mesh size, and fiber volume fraction on the acoustic, thermal, and mechanical properties of these composites to optimize their performance and commercial viability.

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