The Impact of Pine Resin-Epoxy Ratios on Fire Resistance and Acoustic Performance of Banana Fiber Composites

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ABSTRACT

Because of their low environmental impact and biodegradability, composite materials derived from natural fibers and resins have drawn interest as sustainable substitutes for synthetic materials in thermal and acoustic applications. Two promising natural components are banana stem fiber and pine resin, but they need to be modified due to their mechanical limitations and flammability. Epoxy resin is commonly used to enhance structural performance; however, its effects on acoustic and fire resistance properties require further investigation. This study examined how different epoxy resin contents affected the sound absorption and fire resistance of composites made from banana stem fiber and pine resin. Four formulations were created with 10% banana stem fiber and epoxy resin contents of 0%, 3%, 6%, and 9%. The experimental results demonstrated that the burning rate increased significantly with increasing epoxy resin content, from 40.08 mm/min in the epoxy-free sample to 56.824 mm/min in the 9% epoxy sample, indicating decreased fire resistance. Measurements of sound absorption showed that all samples performed better as the frequency increased, reaching a peak at about 3500 Hz. The specimen without epoxy resin showed the highest absorption, and performance marginally declined as epoxy content rose. According to these results, epoxy resin may enhance some mechanical qualities but degrade fire resistance and slightly lower acoustic performance. The findings emphasize how crucial it is to optimize material composition according to the intended application, especially when sound absorption and fire safety are important factors.

Keywords: *Acoustic, banana fiber, epoxy, fire resistance, pine resin.*

I. Introduction

These days, noise has become a major issue in modern life, affecting densely populated areas, transportation, and workplaces. When the sound pressure level surpasses the 20 Hz to 20,000 Hz range, which is the normal limit of human hearing, it is referred to as noise [1],[2]. Continuous noise, particularly if it happens abruptly or without proper hearing protection, can be uncomfortable, lower productivity at work, and negatively affect people's psychological and biological health, leading to issues with the respiratory system, high blood pressure, impaired concentration, and even permanent hearing damage [3]. The World Health Organization (WHO) states that noise levels above 120–140 dBA are harmful to human health [4]. Innovation in soundproofing materials has emerged as a key area of materials technology focus as the value of acoustically healthy living and working spaces grows.

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The development of acoustic materials based on natural fibers is a feasible approach for minimizing the effects of noise while promoting sustainability. High sound absorption coefficient [5], high porosity and tortuosity [6], material thickness, air flow resistivity [7], micro- and nanostructures [8], and environmental resistance [9], including fire and moisture resistance, are the most important requirements for acoustic materials. The stem of the banana fiber is one of the natural materials that exhibits great potential [10]. Additionally, it has been investigated whether using natural resins, like pine resin, in conjunction with epoxy resin can improve the composite's mechanical strength and acoustic absorption [11]-[13]. Therefore, the combination of pine resin-epoxy resin, and banana stem fiber establishes the possibility of producing high-absorption, environmentally friendly, and sustainable acoustic materials.

However, fire resistance is a major obstacle in the development of acoustic materials based on natural fibers. The flammability of organic-based materials restricts their use in construction. As a result, the material composition must be changed to meet the requirements for fire protection and provide the best possible acoustic performance. Controlling the volume fraction of natural and synthetic resin is one strategic approach to producing multifunctional composite materials. This method preserves or even enhances mechanical strength and acoustic performance while achieving the best possible fire resistance.

A study on the addition of a small fraction of DOPO (9,10-dihydro-9-oxa-10-phosphaphenanthrene-10-oxide)-based flame retardant to an epoxy matrix significantly increased the limited oxygen index (LOI) from 25.8% to 33.4% and achieved a UL-94 V-0 classification without compromising mechanical strength, even increasing the elastic modulus to 59.5% [14]. Although the study used synthetic additives, the same principle can be applied to natural resins such as pine resin, which chemically have active carbon groups and aromatic compounds that have the potential to produce a protective carbon layer upon combustion [15]. This demonstrates that composite materials with high sound absorption, fire resistance, and environmental friendliness can be produced by optimizing the volume ratio of pine resin to epoxy.

Although banana stem fiber and pine resin are recognized for their sustainability in composite applications, and epoxy resin is commonly used to improve mechanical strength, there is insufficient research examining the impact of different epoxy resin fractions on the fire resistance and sound absorption characteristics of such natural composites. This gap limits the effective optimization of material formulations for safe and functional thermal-acoustic applications. Furthermore, the objective of this study is to investigate the effect of different pine resin-epoxy ratios on the sound absorption and fire resistance of composites made from banana stem fiber and pine resin. In order to accomplish this, the volume fraction ratios of natural resin (pine resin) and synthetic resin (epoxy) are adjusted to enhance fire resistance without compromising acoustic performance. The use of banana stem fiber, a naturally occurring substance that absorbs sound, in conjunction with epoxy resin and natural pine resin to create a multipurpose composite formulation, is what makes this study novel. By optimizing the resin ratio, this method not only creates sustainable acoustic materials but also increases fire resistance. This study has a wide range of practical applications, particularly in the creation of wall panels, ceilings, and building partitions that must be able to absorb sound and adhere to fire safety regulations.

II. Material and Methods

A. Preparation of Acoustic Materials

The composition of the raw materials used to make acoustic materials is indicated in Table 1 and includes epoxy resin, natural pine resin, and banana stem fiber. 10% is the constant volume fraction of banana stem fiber. The fiber of banana stems is manually separated from the stem, combed, and then allowed to dry in the sunlight. Furthermore, the fiber is sliced into lengths of 5 cm. Meanwhile, a magnetic stirrer is used to heat pine resin and epoxy with the composition listed in Table 1 to 170°C, 400 rpm, and 60 minutes of holding time. The three materials are mixed evenly, then placed in the mold (each for the impedance tube test and the fire resistance test sample) using the hand lay-up method. They are then allowed to dry at room temperature for a full day. Three specimens were made for each treatment, both for fire resistance tests and acoustic tests.

Table 1. Composition of acoustic materials

Specimen code	Volume fraction (%)		
	Pine resin	Epoxy resin	Banana stem fiber
A	90	0	10
B	87	3	10
C	84	6	10
D	81	9	10

B. Test for Fire Resistance

With a test specimen size of 125 x 13 x 3 mm, the horizontal burning test, ASTM D 635-2003 standard, is the fire resistance testing method utilized. Figure 1 displays the testing plan.

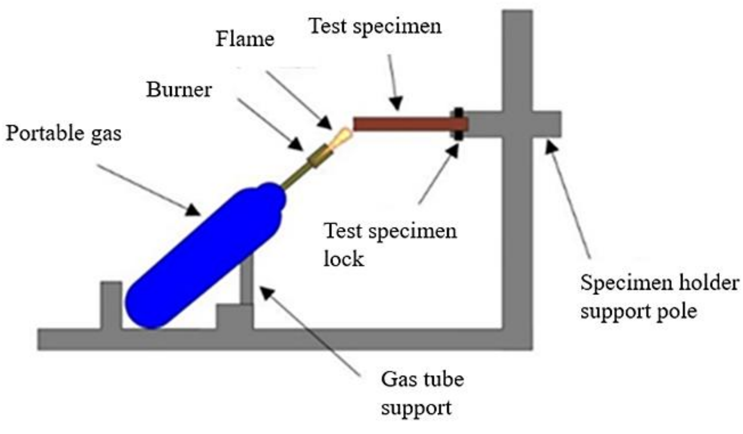

Fig. 1. Fire resistance test scheme

The test specimen is marked with two points at lengths of 25 mm and 100 mm from the end. The burner is then positioned at a 45° angle as illustrated in Figure 2(a). For 30 seconds, the specimen is burned from the end to the 25 mm mark (Figure 2(b)). The specimen is deemed to have failed (lacked fire resistance) if it burns past the 25 mm line in less than 30 seconds. As seen in Figure 2(c), the timer is stopped and then restarted once the flame reaches the final 25 mm mark and is allowed to burn until it reaches the final 100 mm mark

(75 mm). The burning rate is calculated in mm/min based on the distance burned and the recorded time using Eq. (1) [16].

$$V = L / t \quad (1)$$

Where V is the linear burning rate in millimeters per minute (mm/min), L is the length of the specimen that burns between the 25 mm and 100 mm marks (in millimeters), and t is the amount of time (in minutes) that it takes for the flame to spread from the 25 mm mark to the 100 mm mark.

(a) (b) (c)

Fig. 2. (a) Position of the burner at an angle of 450, (b) Initial combustion from point 0 to 25 mm for 30 seconds, and (c) Combustion from point 25 mm to 75 mm.

C. The Acoustic Test

In accordance with the ASTM E1050-98 standard, the noise absorption test (NAC) method was used to perform the acoustic test [17]. This device is in the form of a tube with an inner diameter of 100 mm, a thickness of 5 mm, and a length of 1000 mm. The distance between microphone 1 and the sound source is 200 mm, while the distance between microphone 1 and microphone 2 is 500 mm. The test specimens are 100 mm in diameter and 10 mm thick. The test used two pieces of software: Pulse Labshop for the sound source and Audience for recording and displaying graphics. Figure 3 displays the testing schematic.

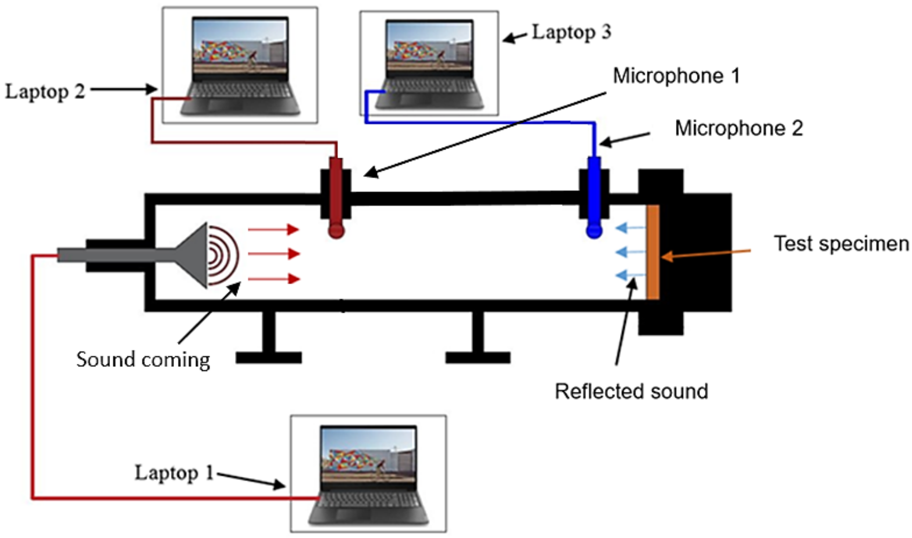

Fig. 3. Acoustic test scheme

The test specimen is fixed on an impedance tube in this experimental configuration. The incident sound originates from Laptop 1, which uses Pulse Labshop, a tune generator software, to produce tones that are played through a speaker with a frequency in the range of 1000-5000 Hz. Microphone 1 records the incident sound, and Audacity software on laptop 2 displays it. A portion of the sound wave is absorbed, reflected, and transmitted when it hits the test specimen. Microphone 2 records the reflected sound, and Laptop 3 displays it. Thus, incoming sound energy, W_i, is divided into three components: W_a, which is the portion of energy absorbed by the material; W_b, which is the portion of energy reflected back; and W_u, which is the energy transmitted through the material, as shown in Eq. (2) [9]. In this experiment, the transmitted sound energy is nearly zero, so that is neglected. The sound absorption coefficient (∝) was determined using Eq. (3). Each experiment was repeated three times to ensure the reliability, consistency, and validity of the research results.

$$W_i = W_a + W_b + W_u \quad (2)$$

$$\propto = \frac{W_i - W_b}{W_i} \quad (3)$$

D. Data Analysis

The outcomes of the fire-resistant and acoustic tests were analyzed using tables, graphs, and statistical tests. To determine whether the pine resin-epoxy ratios had an impact on the composite's fire resistance, a single-factor ANOVA test was employed. A 2-way ANOVA test was used to analyze the acoustic data in order to investigate how sound frequency and pine resin-epoxy ratios affected the sound absorption coefficient.

The simple additive weighting (SAW) approach was used to identify the composite with the optimal fire resistance and sound absorption capabilities. SAW is a method commonly used in determining choices with many criteria. This technique applies the principle of adding the weight values of each choice to all existing parameters [18] and provides recommendations based on the highest score obtained from the weighting and normalization process [19]. In this method, the evaluation of maximization and minimization criteria is known as the benefit criteria and cost criteria [20].

III. Results and Discussions

A. Fire Resistance

The fire resistance test results are shown in Table 2, and the average values are plotted in the graph in Figure 4. Table 4 depicts an ANOVA that demonstrates how much the pine resin-epoxy fraction influences fire resistance. According to Table 1, Table 2, and Figure 4, pine resin significantly increased the composite's fire resistance. With a linear burning rate of 40.03 mm/min, specimen A, which contained 90% pine resin, demonstrated the best fire resistance performance when compared to the other specimens. It was known that pine resin contained thermostable natural polymerized components like rosin and turpentine, as well as aromatic compounds that could slow down the rate of burning. It has been suggested that one of the key ways to improve fire resistance is through the mechanism of char formation by aromatic components in natural materials [21]. In this instance, the compounds in pine resin also had the capacity to create a char layer, or carbonized layer, during combustion, which shielded the inner surface and prevented heat and oxygen from diffusing. This demonstrated how crucial it is for a protective carbon layer to form in bio-resin-based composites in order to slow the spread of flames [22]-[24].

The burning rate increased significantly from 40.03 mm/min to 56.824 mm/min as the epoxy resin content in the specimen increased from 0% (Sample A) to 9% (Sample D). This indicates that in this particular formulation, epoxy resin tended to reduce fire resistance. One possible explanation is that the epoxy resin used in this study was not modified with flame retardants, and as a thermosetting polymer, it can be inherently flammable and capable of producing high heat release during thermal degradation. Consequently, the presence of epoxy promoted faster combustion and accelerated fire spread [25].

Table 2. Experimental data of the fire resistance test

Specimen code	Burning length (mm)	Burning time (minutes)	Linear burning rate (mm/minutes)
A1	75	1.7	44.117
A2	75	2.01	37.313
A2	75	1.94	38.660
Average A			40.030
B1	75	1.40	53.571
B2	75	1.35	55.555
B3	75	1.37	54.744
Average B			54.623
C1	75	1.33	56.39
C2	75	1.35	55.555
C3	75	1.37	54.744
Average C			55.563
D1	75	1.34	55.970
D2	75	1.30	57.251
D3	75	1.30	57.251
Average D			56.824

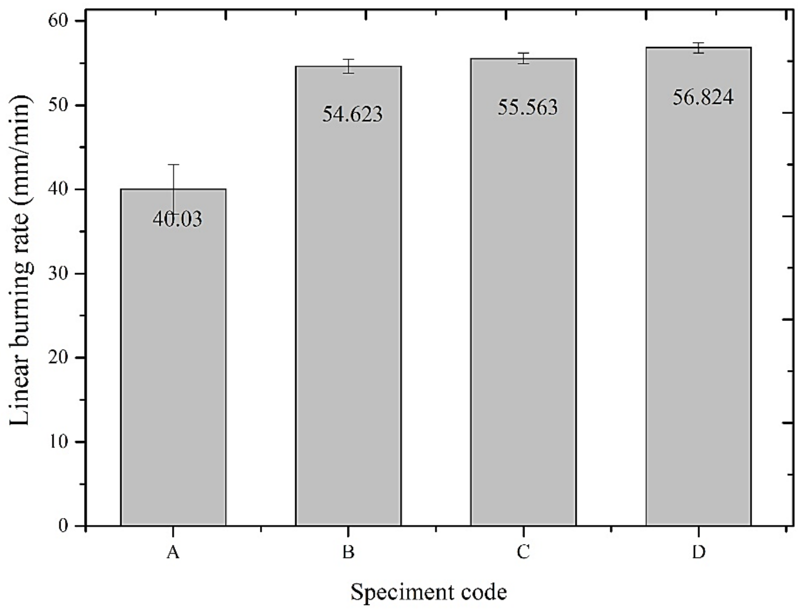

Fig. 4. Linear burning rate of the specimen

Table 3 provides an overview of ANOVA used to assess the effect of pine resin-epoxy ratios on fire resistance. The F and P tests were used to evaluate the results. While the F test was performed by comparing the F table with the calculated F [26], the P test compares the

P value with a specific level of significance [27]. The ANOVA test produced an F value of 48.9186, which is much greater than the critical F-value (4.0661), and a P-value of 1.72 × 10^{-5}, which is much smaller than the significance level of 0.05. These results indicate that there is a significant difference between sample groups, so that the null hypothesis (H_0), namely that there is no difference in the average fire resistance between groups, is rejected. Stated differently, fire resistance is significantly influenced by the pine resin-epoxy ratio; the higher the pine resin content, the greater the composite's fire resistance.

Table 3. Analysis of variance

Source of variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between groups	557.6954	3	185.8985	48.9186	1.72E-05	4.0661
Within groups	30.4012	8	3.8001			
Total	588.0967	11				

B. Sound Absorption Coefficient

Table 4 displays the average sound absorption coefficient of the specimens at various frequencies, which was presented in a graph as illustrated in Figure 5. Meanwhile, Table 5 presents ANOVA results for the association between sound frequency, pine-epoxy ratios, and sound absorption coefficient. The sound absorption coefficient (α) is a crucial factor in acoustic design, as it indicates how effectively a material absorbs sound energy. The range of the α value is 0 (no absorption) to 1 (perfect absorption). Sound frequency and the pine-epoxy ratios of materials significantly affect how well sound is absorbed, as shown in Table 5 (with a 5% significance level, F > F*crit*, for sound frequency and pine-epoxy ratios), but not on their interaction. The variation in sound frequency influenced the acoustic panel's sound absorption coefficient [28]. The sound absorption coefficient increased at specific frequencies (1000–2000 Hz and 2500–4000 Hz), indicating that the material absorbed sound more effectively at certain frequencies. The resulting sound absorption coefficient varied from 0.11 to 0.77.

Table 4. Average of experimental data for the acoustic test

No	Frequency (Hz)	Average sound absorption coefficient (α) of acoustic material (three times repetition)			
		A	B	C	D
1	1000	0.18	0.14	0.14	0.11
2	1500	0.28	0.25	0.24	0.22
3	2000	0.37	0.36	0.33	0.31
4	2500	0.29	0.27	0.25	0.21
5	3000	0.37	0.34	0.29	0.24
6	3500	0.66	0.60	0.58	0.56
7	4000	0.77	0.67	0.65	0.59
8	4500	0.67	0.64	0.61	0.59
9	5000	0.66	0.61	0.58	0.57
Average		0.47	0.44	0.41	0.38

The composition of a material is closely related to the sound absorption coefficient (α) because the physical features and internal structure of the material affect its ability to absorb sound energy. Overall, material A had the largest sound absorption coefficient, followed by materials B, C, and D at all frequency levels. This indicates that the higher the epoxy resin content, the lower the sound absorption coefficient. Materials with increased pine resin content exhibited higher α values, particularly at high frequencies (≥3500 Hz). Material A (90% pine resin, 0% epoxy, 10% banana fiber) had the highest α value across multiple frequencies and reached a peak at a frequency of 4000 Hz with α = 0.77. This confirmed that pine resin, a natural matrix material, had a more porous and elastic structure, making it more effective in absorbing sound waves.

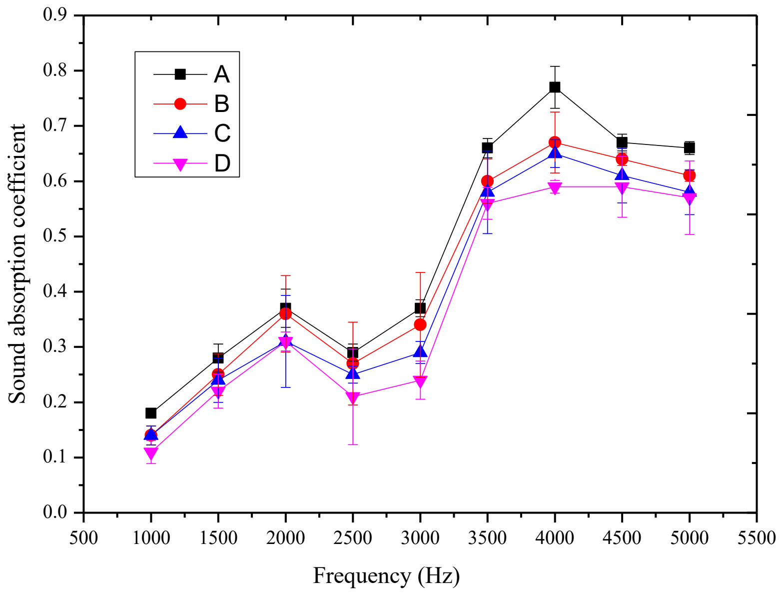

Fig. 5. Sound absorption coefficient of specimen

Table 5. ANOVA of the relationship between sound frequency and pine-epoxy ratios on the sound absorption coefficient

Source of variation	*SS*	*df*	*MS*	*F*	*Fcrit*
Frequency	3.7274	8	0.4659	242.6262	2.0698
The pine-epoxy ratios	0.1249	3	0.0416	21.6837	2.7318
Interaction	0.0275	24	0.0011	0.5972	1.6694
Within	0.1382	72	0.0019		
Total	4.0181	107			

Material D (81% pine resin, 9% epoxy) demonstrated the lowest α value across nearly the entire frequency range. This suggested that incorporating rigid, nonporous epoxy resin prevented the acoustic energy from diffusing into the material structure, thus enhancing the reflected sound. The proportion of banana stem fiber (10%) remained unchanged in all samples, meaning that the differences in α primarily resulted from variations in the amounts of pine resin and epoxy. Banana fiber was absorbent, but its efficiency largely depended on the type of matrix (resin) employed. Comparable findings were documented: the acoustic characteristics of composites created from natural waste fibers (cotton, coconut, and sugarcane) combined with bio-based epoxy resin indicated that a higher fiber volume fraction (lower epoxy resin content) enhanced the sound absorption coefficient [29]. Employing natural resin in natural fiber composites yielded a greater sound absorption coefficient than synthetic epoxy resin. This was due to the nature of natural resin, which was more compatible with the fiber pore structure, resulting in more effective sound wave absorption.

The microstructural interaction between epoxy resin and natural pine resin significantly influences porosity and, in turn, modulates the mechanisms of sound wave dispersion and absorption [30],[31]. In this case, pine resin introduces micro-voids and heterogeneities that enhance acoustic damping via viscous and thermal losses. In contrast, increasing epoxy content reduces porosity and suppresses these mechanisms by forming a dense, rigid matrix, thereby reducing internal sound wave attenuation. Optimal acoustic performance is achieved by balancing these resins to retain beneficial porosity while maintaining structural integrity.

C. Optimal Condition

Four composites with different compositions (A, B, C, and D) were examined and assessed using the burning rate and the sound absorption coefficient. The sound absorption coefficient, treated as a benefit criterion, is averaged across all relevant frequencies, with higher values indicating better acoustic performance. In contrast, the burning rate is a cost criterion, where lower values are preferred due to improved fire resistance. For this analysis, it is assumed that both criteria are equally important, assigning each a weight of 0.5: sound absorption (W1) = 0.5 and burning rate (W2) = 0.5. Table 6 shows a summary of the optimization evaluation using SAW. As with its highest weight score, as shown in Table 6, the best combination of acoustic performance and fire safety is found in Specimen A, which is made up of 90% pine resin, 0% epoxy resin, and 10% banana fiber. It not only satisfies functional requirements but also conforms to sustainable and fire-resistant material design due to its high sound absorption capacity and noticeably low burning rate. Its makeup demonstrates how bio-based materials can provide benefits for both performance and the environment.

Table 6. The results of the SAW calculation

Specimen	Avg. sound absorption	Avg. burning rate	Normalized sound absorption (max =0.47)	Normalized burning rate (min = 40.03)	Weighted score
A	0.47	40.03	1	1	1
B	0.44	54.623	0.936	0.733	0.835
C	0.41	55.563	0.872	0.720	0.796
D	0.38	56.824	0.809	0.704	0.757

IV. Conclusions

The results of the study demonstrate that the acoustic absorption and fire resistance characteristics of bio-based acoustic composites are significantly impacted by the addition of epoxy resin. As the epoxy resin content increased from 0% to 9%, there was a discernible trend of rising burning rates, indicating a decline in fire resistance. The inherent flammability of epoxy resin, which accelerates flame propagation and increases heat release during degradation, is highlighted by this behavior. Although all specimens showed improved sound absorption with increasing frequency, the composite without epoxy resin showed the best acoustic performance, suggesting that epoxy somewhat reduces the material's capacity to absorb sound. These results address the primary research question by demonstrating that epoxy resin can improve the structural integrity of composites at the price of reduced fire safety and acoustic efficiency. This highlights how important it is to balance composition and carefully select materials when making composites for acoustic applications, particularly in situations where fire safety is a concern. Based on the SAW method, which considers equal importance between sound absorption and burning rate, Specimen A (90% pine resin, 0% epoxy resin, 10% banana fiber) was identified as the optimal composition, offering the best trade-off between high acoustic performance and low flammability, making it a promising candidate for safe and effective indoor acoustic applications. However, the mechanical performance and long-term behavior of these composites in real-world situations remain unclear. Further research is needed to determine alternative flame retardants that can be added without compromising the composites' acoustic properties, long-term durability, and biodegradability.

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