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Utilizing Agricultural Waste Materials for the Development of Sustainable Sound Absorption Materials

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ABSTRACT

Environmental pollution is escalating due to inadequate waste management, with the open burning of agricultural waste being a significant contributor. This process releases various harmful gases into the environment. This study introduces an innovative approach to creating sound absorption materials using agricultural by-products, specifically paddy straw and coconut coir, along with newspaper by-products. The research was conducted in two phases: first, the production of sound absorption panels with different densities and adhesive quantities, and second, the evaluation of these panels' sound absorption capabilities through laboratory experiments. The impedance tube test was used to determine the sound absorption coefficient (SAC). The results showed effective sound absorption, especially at lower frequencies ranging from 125 Hz to 6300 Hz. Notably, paddy straw and coconut coir exhibited significant sound absorption values at 1,000 Hz (0.59 and 0.52, respectively). This study highlights the potential of paddy straw and coconut coir as sustainable, cost-effective materials for sound absorption panels. These natural materials demonstrate excellent sound-absorbing properties, making them suitable for various applications such as classrooms, sound recording rooms, auditoriums, and theaters at low to medium frequencies.

INTRODUCTION

An acoustic panel serves as an effective sound-absorbing solution to mitigate background noise, minimize reverberation, and address echoes within a given space. Typically, these panels are sizable, soft-furnished installations strategically positioned to enhance sound quality (Carme et al. 2017, Yu et al. 2014). Constructed from a combination of foam and fabric, acoustic panels can be customized in various shapes and sizes to complement the aesthetic design of the room. Their primary function is to eliminate lingering sounds within a space (Carme et al. 2016, Fan et al. 2013, Gao et al. 2017). When appropriately installed, acoustic panels can absorb or diffuse sound right from its initial point of reflection. These sound-absorbing materials find application on the ceilings and walls of venues like auditoriums, concert halls, and theatres, where unwanted reverberation is highly undesirable. The incorporation of sound-absorbing materials in these spaces ensures that sound reflected from rigid surfaces is absorbed, thereby suppressing reverberation (Chen et al. 2011, Emms & Fox 2001, Rubino et al. 2023).

Typically, acoustic panels are crafted with a timber frame and multiple layers of acoustic foam. Foam is particularly effective as it absorbs frequencies at the surface, generating resonance within the cavity. Vertical panels, in general, play a crucial role in mitigating sound transfer within a space, preventing it from traveling across the room (Emms 2000, Rubino et al. 2023, Tsukamoto et al. 2020). Additionally, vertical panels contribute to reducing background noise to an acceptable level (Fig. 1). While achieving complete removal of background noise may require floor-to-ceiling partitions or distancing oneself from the noise source, vertical panels significantly aid in sound reduction (Redondo et al. 2021, Gao et al. 2017).

In polymeric materials, sound absorption occurs through the conversion of sound waves into heat. This process is crucial for soundproofing, with foamed plastics being the preferred choice due to their characteristic impedance similar to air. Effective soundproofing is essential for controlling unwanted noise. Acoustic treatment plays a key role in addressing three aspects of sound that can present challenges (Gao et al.

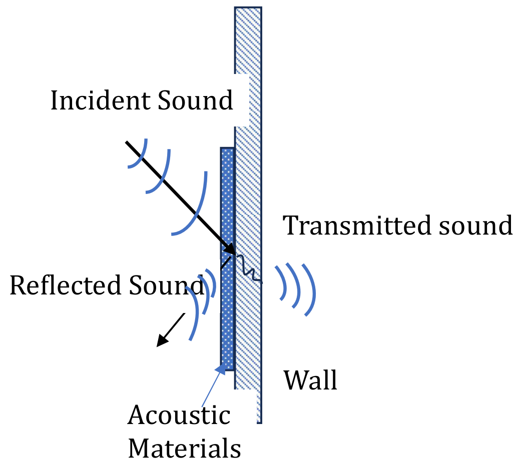

Fig. 1: Sound Transmission.

2017): reflection, reverberation, and resonance. Reflection is a common issue in various spaces where sound waves encounter surfaces, such as walls and furniture. Some surfaces absorb sound waves, while others cause them to bounce off, potentially deflecting away from the intended target, especially in places like school auditoriums, concert venues, and churches. Reflection can lead to reverberation. Reverberation occurs when multiple sound waves bounce off surfaces and converge, creating an echoey effect in certain rooms (Lam & Gan 2016, Lam et al. 2018). This phenomenon is more pronounced in large, empty spaces without sufficient sound-absorbing elements. Reverberation not only affects the clarity of music or speech but also interferes with communication in places like restaurants. Resonance is the amplification of sound when an object or material vibrates at its natural frequency upon encountering a sound wave. This can lead to boomy and distorted sounds, creating acoustic challenges for facilities.

To counter these issues, sound-absorbing acoustical panels and soundproofing materials are employed to eliminate sound reflections. Common materials include open-cell polyurethane foam, cellular melamine, fiberglass, fluffy fabrics, and other porous materials (Pàmies et al. 2018, Wang et al. 2018). These materials come in varying thicknesses and shapes to achieve different absorption ratings based on specific sound requirements. Various sound absorption materials are available, such as acoustical foam panels, paintable acoustical wall panels, fabric-wrapped panels, acoustical wall coverings, ceiling tiles, baffles, banners for ceilings, fiberglass blankets, and rolls, among others. These materials offer diverse options for effectively managing sound in different environments (Fig. 2).

MATERIALS SPECIFICATIONS AND THEIR BEHAVIOUR

Sound absorber samples were fabricated using dried paddy straw, coconut coir, and waste paper. The experimental results indicate that these agricultural by-products exhibit promising characteristics as sound absorbers, establishing them as a viable alternative among various natural fibers. Natural fibers, such as those derived from paddy straw, coconut coir, and waste paper, offer several advantages over synthetic materials like glass fiber and mineral-based substances. Notably, natural fibers are cost-effective, lightweight, and environmentally friendly (Murao &

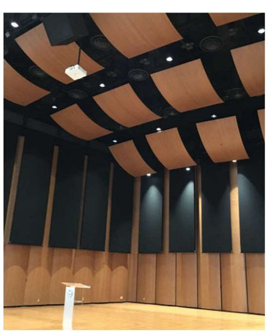

Fig. 2: Various sound-absorbing panel systems.

Nishimura 2012, Murao et al. 2017). When compared to glass fiber and mineral-based synthetics, they prove to be more sustainable options. Additionally, natural fibers align with principles of environmental sustainability by providing a resource that can be continually produced to meet present needs without compromising the ability of future generations to meet their own requirements (Kwon & Park 2013, Pàmies et al. 2018). This inherent sustainability adds to the appeal of natural fibers as sound absorbers, making them not only effective but also in harmony with eco-friendly practices.

Paddy Straw Properties and Composition

Paddy straw, a readily available natural fiber in Southeast Asia, has been widely utilized in various applications such as roofing, rope production, animal feed, and floor mats over the past decade. However, its potential as a sound absorber panel has not been thoroughly explored until now. This paper aims to investigate the feasibility of utilizing dried paddy straw fiber as a raw material for sound-absorbing materials, a prospect motivated by its abundant availability (Carme et al. 2017, Kwon & Park 2013). Paddy straw was specifically chosen as the raw material due to its extensive availability, with a global annual production of 580 million tons. Being an annually renewable, abundant, and cost-effective source of natural cellulose fibers, rice straw presents an opportunity for creating high-value fibrous applications. This not only enhances the value of rice crops but also contributes to the sustainability of fiber resources and benefits the environment (Nelson & Elliott 1992, Huang et al. 2011, Xiao et al. 2020).

The investigation into paddy straw reveals its suitability for acoustic panels, attributed to its high elasticity and hollow structure. The properties of paddy straw fibers demonstrate superior characteristics compared to other natural cellulose fibers derived from agricultural by-products (see Table 1). The usage of rice straw depends on the extensive study of its characteristics such as the physical properties of the rice straw, thermal properties, and chemical composition. A comprehensive characterization of rice straw is indispensable for conducting life cycle analyses and efficiency calculations in applications involving this versatile material.

As per the study conducted in previous work, it can be identified that the density of the rice straw varies from one form to other forms. When the rice straw is directly collected from the agriculture field, the density varies from 13 to 18 kg/m^3 in dry conditions. In the case of chopped rice straw, with lengths varying from 5 to 10 mm, the density varies from 55 to 120 kg/m^3. The specific experiments discussed in this context involved paddy straw chopped into lengths of 2.5 to 5.0 cm. In these experiments, the mean bulk density, true density, and porosity of the chopped paddy straw were determined. The results indicated a mean bulk density of 43.5±5 kg/m^3, a true density of 53±2.5 kg/m^3, and a porosity of 80.32±5% (see Table 2). These findings provide valuable insights into the physical characteristics of the chopped paddy straw, offering essential data for further understanding its potential applications, especially in the context of sound absorption materials (Hansen et al. 2012, Hongo & Serizawa 1999, Xu et al. 2018).

The pressure needed to compact the chopped paddy straw varied, correlating with a bulk density range of 74.54 to 475.8 kg/m^3, spanning from 65.4 to 1389.1 kPa. Within this range, the highest compaction ratio reached 6.36, with density and relaxation ratios of 0.78 and 1.43, respectively. This resulted in a significant percentage volume reduction of 465%. These parameters provide insights into the compressibility of the chopped paddy straw, essential for understanding its behavior under different pressure conditions. Moreover, the study delved into the impact of compression levels on the final moisture content of paddy straw. This investigation is crucial for comprehending how the compaction process influences

Table 1: Properties of Paddy Straw.

S. No.	Properties	Value
1	Heating value, MJ/Kg (dry basis)	17.12
2	Proximate analysis (wet basis, wt. %)	
i	Moisture	8.19
ii	Ash	12.14
iii	Volatiles	65.24
iv	Fixed carbon	12.91
3	Thermogram Vimetrical analysis, wt. %	
i	Hemicellulose	33.10

Table 2: Composition of Paddy Straw.

S.No.	Component	Percentage (%)
1	Moisture	21
2	Lignin	14.45
3	Cellulose	33
4	Nitrogen-free extract	4.21
5	Ash	18.5
6	Silica	14.23
7	Calcium	0.16
8	Phosphor	0.11
9	Potassium	0.23
10	Magnesium	0.12
11	Sulphur	0.09
12	Cobalt	0.04 (mg/kg)
13	Copper	0.40 (mg/kg)
14	Manganese	0.50 (mg/kg)

the moisture characteristics of the material, offering valuable information for various applications, including those related to sound absorption materials or other potential uses (Arenas 2007).

Waste Paper Properties and Composition

Basis weight is the weight of paper measured in pounds per ream (500 sheets). Paper and paperboard, available in a multitude of varieties, exhibit a wide range of properties. Among the thousands of paper types, some properties show only minor variations, while others differ significantly. To maintain consistency, all tests are conducted under standard conditions (24°C or 75°F; 50 percent relative humidity) as paper properties are known to change with moisture content. The surface pattern of paper can vary from smooth to slightly rough (Park & Eom 1997).

The surface sheen of paper can range from glossy (with the highest shine) to luster (medium shine) to matte (dull). In glossy papers, dark areas appear darker than in matte papers, and excessive-gloss can lead to distracting reflections. The key optical properties of paper include brightness, color, opacity, and gloss. Brightness, specifically, refers to the degree to which white or near-white papers reflect light in the blue end of the spectrum. This reflectance is measured by an instrument illuminating paper at a 45° angle with a wavelength of 457μ (microns). Brightness, measured in this way, closely correlates with subjective assessments of the paper's relative whiteness. Opacity, brightness, whiteness, color, and gloss are the five main optical properties influencing the visual perception of a printed sheet. Paper fibers, characterized by high porosity, can be easily manufactured with controlled properties, making them suitable for sound absorbers. Additionally, paper is biodegradable, poses no health risks, and can be shaped into various forms with ease. These qualities make the paper an ideal material for sound absorption applications (Tong & Tang 2013).

COCONUT COIR PROPERTIES AND COMPOSITION

Coconut fiber, derived from the husk of coconuts, stands out as a prominent fibrous waste generated by the cultivation of coconuts. Annually, the world produces a substantial 30 million tons of coconuts, particularly abundant in the coastal regions of tropical countries. The composition of the coconut husk comprises 30% fiber and 70% pith, boasting high lignin and phenolic content. The elevated lignin content renders coconut fiber exceptionally elastic, durable, and resistant to rotting (Park & Eom 1997, Hongo & Serizawa 1999, Tong et al. 2015).

Following the extraction of coconut meat and water, what remains is the fibrous coconut husk. When mature and dried, this husk can be further processed to yield another valuable product known as coconut coir. Coconut coir proves to be an excellent addition to gardening practices, enhancing the texture of clay or sandy soil, and promoting sturdy root growth in plants. Moreover, it facilitates access to additional nutrients during the feeding and watering processes. The versatility of coconut coir extends to various applications, including upholstery, agriculture, horticulture, hydroponics, and geo-textile, making it a valuable and sustainable resource in multiple industries.

Coconut coir's versatility extends to various applications beyond gardening. It can be transformed into ropes, twines, brooms, brushes, doormats, rugs, and more. Despite its multifunctionality, coconut coir has gained significant recognition in hydroponics, a gardening method that doesn't rely on soil for plant growth.

Coconut coir possesses properties that make it well-suited for hydroponics. These include:

1. **High Water Absorption:** Coconut coir has a remarkable ability to absorb and retain water, providing consistent moisture to plants in hydroponic systems.
2. **High Nutrient Absorption:** It can absorb and retain nutrients effectively, promoting the healthy growth of plants in the absence of soil.
3. **High Durability:** Coconut coir is durable and can withstand the conditions of hydroponic systems, ensuring a longer lifespan and sustained support for plant growth.
4. **Better Air-to-Water Ratio:** It offers an optimal balance between air and water, creating an environment conducive to root development and nutrient absorption.

These characteristics make coconut coir an excellent choice for hydroponics, contributing to its popularity in modern soilless cultivation systems. Its use in hydroponics has become widespread due to its positive impact on plant health and overall crop yield (see Table 3).

Some advantages of coir fibers include insect insect-proof, resistant to fungi and decay, provide good insulation against temperature and sound. They remain unaffected by external factors like humidity. Compared to other typical natural fibers, coconut fiber has higher lignin and lower cellulose and hemicellulose, together with its high microfibrillar angle, offers various valuable properties, such as resilience, strength, and damping, wear, resistance to weathering, and high elongation at break.

MATERIALS

Raw Material Preparation and Manufacturing of Panel

The construction of an absorber sample involves two distinct

Table 3: Physical and Chemical Properties of Coconut Coir Fiber.

Sl. No.	Physical Parameter		Values
1	Ultimate length		0.6 mm
2	Diameter/width		16 micron
3	Single fiber	Length	5 to 8 inches
		Density	1.42 g/cc
		Tenacity	10 g/tex
4	Breaking Elongation		20 mm
5	Moisture regains at 65% RH		10.2%
6	Swelling in water		5% in diameter
Sl.No.	Chemical Parameter		Values
1	Water soluble		5.15%
2	Pectin & related compounds		3.10%
3	Hemi-Cellulose		0.22%
4	Cellulose		41.44%
5	Lignin		44.84%
6	Ash		2.20%

stages: material cutting and sample preparation. In the material cutting stage, the raw material is processed into

Table 4: Sample specifications.

Parameter	Values
Diameter (d) of the samples	30 mm & 100 mm
Thickness of the samples	25 mm
Materials	Paddy straw, waste paper, and coconut coir
density	400 kg/m^3

2mm to 5mm lengths, as illustrated in the process flow chart. The preparation stage involves blending the raw material with various compositions of binders. The composites are defined by a weight/area of 400g/m^2, a diameter of 30mm, and a dimension of 100mm.

Paddy straw, waste paper, and coconut coir are precisely cut into small pieces ranging from 2mm to 5mm. The total weight of waste paper, coconut, and paddy straw is determined to achieve the desired concentration for a weight/area of 400g/m^2 (see Table 4). The composition of the panel primarily consists of fibers, ensuring that other factors do not affect the performance of the acoustic panel. The adhesive additives are the only additional ingredient

Fig. 5: Paddy Straw, Coconut Coir, and Waste Paper Panel (100 Mm).

Fig. 6: Paddy Straw, Coconut Coir and Waste Paper Panel (30 Mm).

applied during the panel manufacturing process. The panels are ideally bonded using adhesive additives, and the size of the panels is standardized according to impedance tube testing requirements (Figs. 5 & 6). This meticulous approach to material selection, cutting, and preparation aims to create acoustic panels with optimal performance characteristics.

Therefore, this work aims to study the potential use of Paddy Straw, Waste Paper, and coconut coir as a sound absorption material to replace synthetic materials such as glass wool, mineral wool, felts, or polyester fibers in the current market. This study revolved around the sound absorption properties of the Paddy Straw, Waster Paper, and Coconut coir fibers together with its characteristics and the form of the coir fibers.

METHODS

Impedance Tube

The research employs the two-microphone transfer function method as outlined in the International Standard ISO 10534-2 (1998) to collect data through the impedance tube method. This method offers a swift means of obtaining normal incidence factors from small samples, facilitating the assembly and disassembly of materials on the impedance tube equipment (Fig. 7).

The impedance tube method serves as the primary approach for gauging the sound absorption characteristics of fibrous materials. Utilizing the Impedance Tube Kit (Type 4206), which covers the frequency range of 50 Hz to 6.4 kHz, this method is applicable to various materials such as hood liners, headliners, fiberglass, mineral fiber, cellulose boards or blankets, as well as other fibrous materials, foam products, facing materials, fabrics, papers, and screens. The apparatus accommodates samples of up to 100 mm in diameter and 6 inches in thickness.

Testing of Impedance Tube

A sound source, typically a loudspeaker, is positioned at one end of the impedance tube, while the material sample is placed at the opposite end. The loudspeaker emits broadband, stationary random sound waves, which propagate within the tube and interact with the sample, leading to absorption. The schematic diagram illustrates the impedance tube setup employing the two-microphone transfer function method.

The interaction of sound waves within the tube generates a standing-wave interference pattern due to the combination of forward- and backward-traveling waves. By measuring sound pressure at two fixed locations and utilizing a two-channel digital frequency analyzer to calculate the complex transfer function, it becomes feasible to determine sound absorption, reflection coefficients, and the normal acoustic impedance of the material. The frequency range suitable for measurement depends on the tube diameter and microphone spacing.

In both large and small tube setups, the positioning of microphones is crucial for accurate measurements. Flush mounting of microphones prevents leakage, ensuring precise results. The impedance tube method is favored for its compactness and cost-effectiveness. It adheres to ISO and ASTM standards and is ideal for analyzing small objects exposed to normal sound waves.

Test Procedure

The test procedure entails measuring the normal incidence of sound absorption of acoustical products within an impedance tube apparatus. The apparatus comprises a tube with two microphones mounted on the sidewall, a loudspeaker affixed at one end, and a sample holder at the other end. Tube diameter selection is based on the desired frequency range: 100 mm for frequencies between 50 and 1,600 Hz, 57 mm for frequencies between 200 and 3,150 Hz, and 29 mm for frequencies between 500 and 6,300 Hz.

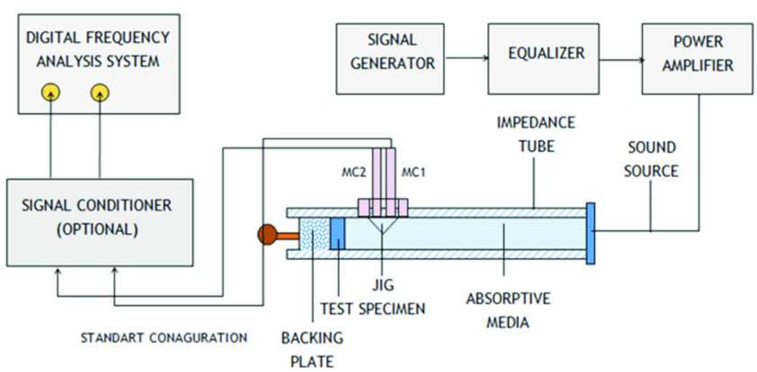

Fig. 7: Impedance Tube Kit Type 4206.

Test specimens, tailored to fit snugly into the sample holder, are subjected to the broadband sound generated within the tube. Sound amplitude and phase are measured by the microphones and a two-channel Fast Fourier Transform (FFT) analyzer. Multiple test specimens from each product are evaluated to ensure accuracy, with results averaged for comprehensive analysis.

RESULTS AND DISCUSSION

The test for sound absorption was conducted using an impedance tube, with the results presented in Fig. 8. The test samples, derived from the original molded panel with dimensions of 30mm x 100mm, included paddy straw, coconut coir, and waste paper. The samples underwent testing at different sound frequencies: 125Hz, 250Hz, 500Hz, 1000Hz, 2000Hz, 2500Hz, 3150Hz, 4000Hz, 5000Hz, and 6000Hz.

The sound absorption coefficient values for paddy straw, coconut coir, and waste paper are provided in Figs. 8, 9 and 10, respectively. These values correspond to varying densities ranging from 250 to 800 kg/m^3. The comprehensive testing across different frequencies and densities offers valuable insights into the acoustic performance of each material, aiding in the assessment of their suitability for sound absorption applications.

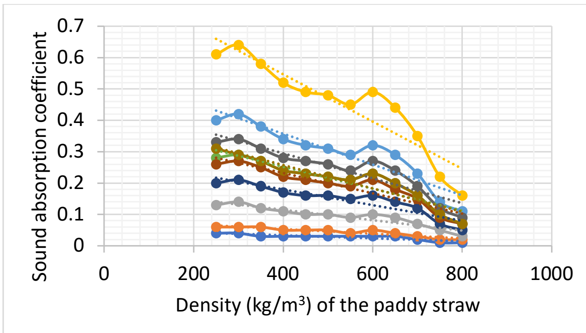

Fig. 8: Sound absorption coefficient for Paddy straw.

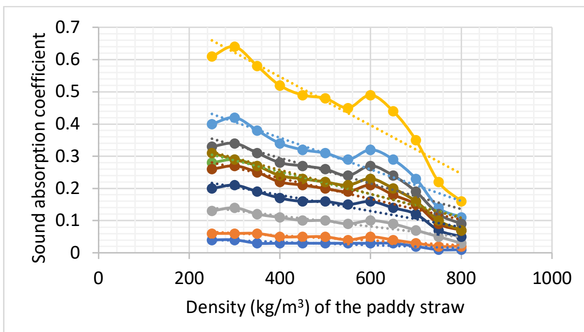

Fig. 9: Sound absorption coefficient for Coconut coir.

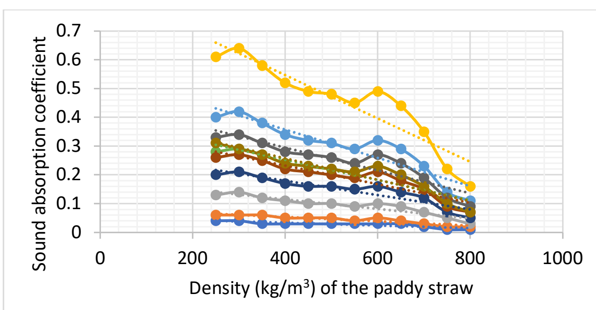

Fig.10: Sound absorption coefficient for waste paper.

The critical property under consideration is the normal incidence sound absorption coefficient, which is a function of frequency and ranges between zero and one. The sound absorption coefficient represents the percentage of sound energy absorbed by the material sample and is a primary indicator of how an absorber material will perform in a

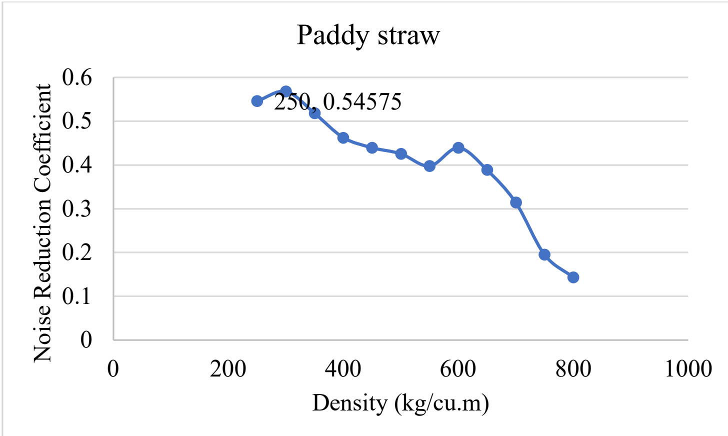

Fig.11: NRC value for paddy straw sample.

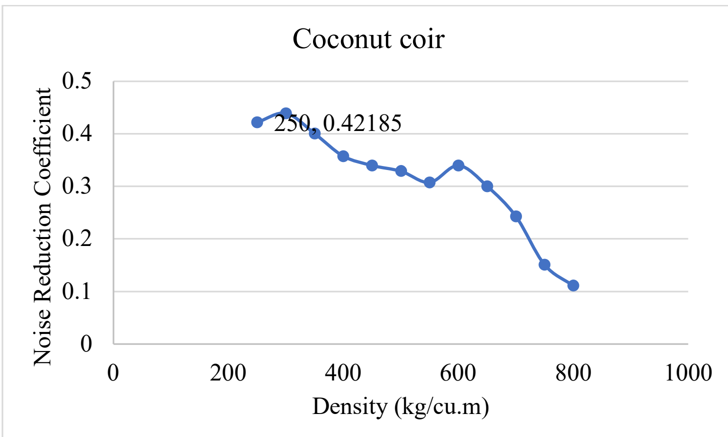

Fig. 12: NRC value for coconut coir sample.

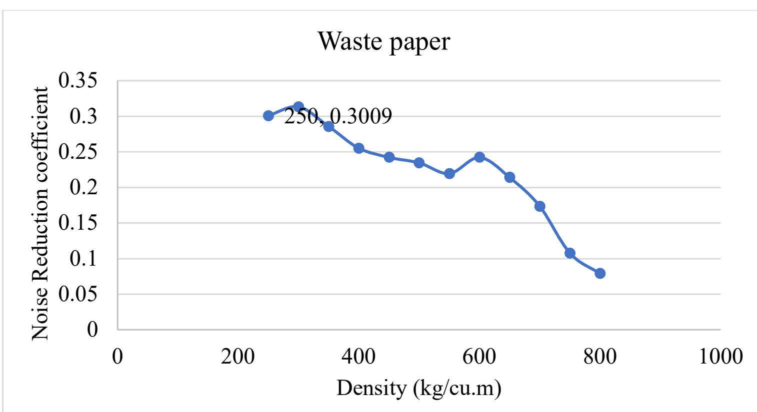

Fig. 13: NRC value for the waste paper sample.

given environment. Sound absorbers made from agricultural byproducts, such as paddy straw, waste paper, and coconut coir, exhibit excellent properties for reducing sound and are commonly used for self-adhesive sound insulation. However, the quality of acoustic panels is crucial for them to realize their full potential as sound absorbers and effectively protect against noise. Besides high-quality materials, the installation of sound absorbers plays a crucial role in the effectiveness of soundproofing or acoustic treatment.

Notably, adhesives like spray glue or conventional assembly adhesive may not always work well when installing sound absorbers. The amount and type of adhesive used can impact the sound absorption quality of the sample, and finding the appropriate dosage to securely attach the absorber to a support surface can be challenging. The type of adhesive used may need to vary for different materials, as observed in the study where the same adhesive worked well for paddy straw and coconut coir but not for waste paper. In the process of producing and processing the samples from paddy straw, waste paper, and coconut coir, the relationship between density and sound absorption coefficients was examined. Increasing density resulted in fluctuating or slightly increased sound absorption coefficients at low frequencies, primarily due to the creation of small pores in the interior sample, making it hard for low-frequency acoustic waves to enter. However, improper compression in the manufacturing process may block the acoustic advantages of porous materials, resulting in poor sound absorption properties at both low and high frequencies. The study concludes that increasing density only insignificantly improves sound absorption properties.

Despite conventional materials having a higher sound absorption coefficient compared to agricultural byproducts, panels made from paddy straw, waste paper, and coconut coir exhibited significant performance in terms of sound absorption properties. Lower-density samples of these agricultural byproducts demonstrated higher sound absorption coefficients and noise reduction coefficients (NRC) compared to higher-density samples. The NRC values for different densities of paddy straw, coconut coir, and waste paper samples are presented in Fig. 11, 12, and 13, respectively. This observation suggests that sound absorption efficiency increases with a decrease in density and vice versa.

In the experimental results, the absorption coefficient of Paddy Straw and Coconut Coir panels was notably high, reaching values close to 0.88 and 0.82 at a density of 250 kg/m3, respectively. The performance aligns with expectations. Conversely, the waste paper sample exhibited a slightly lower sound absorption coefficient value of 0.31 at the same density. Similarly, the noise reduction coefficient values for the samples followed a similar trend as the sound absorption coefficient values.

The sound absorption panel made by paddy straw demonstrated and showed superior performance in sound absorption properties compared to the other samples. The high absorption coefficient values, especially for Paddy Straw and Coconut Coir panels, suggest that these materials can be considered effective sound-absorbing materials. A crucial aspect highlighted in the conclusion is the positive relationship between frequency and sound absorption coefficients for Paddy Straw, Waste Paper, and Coconut Coir materials. The results steadily fell within the 0.70 or higher range, indicating a very high positive correlation between these variables. This correlation underscores the effectiveness of the materials across different frequencies, contributing to their overall suitability as sound absorbers.

CONCLUSION

The experiment demonstrates that natural fibers, particularly Paddy Straw, can serve as a viable alternative sound absorber among various other natural fibers. The choice of the methylcellulose binder was found to influence the absorption coefficient. However, it's noted that the performance, especially at lower frequencies, could be further enhanced by increasing sample thickness or coupling with a perforated panel facing. These aspects will be explored in future work by adjusting thickness and utilizing suitable adhesives, as well as incorporating an optimal number of perforations.

Key findings from the experiment include:

1. Paddy Straw shows better sound absorption performance at higher frequencies than at lower frequencies. Whereas waste Paper shows better sound absorption performance in the range of (125-1000 Hz) than at higher frequencies.
2. Coconut Coir demonstrates better sound absorption performance in the range of (1000-6300 Hz) than at higher frequencies. Increasing density has also an insignificant impact on improving the sound absorption properties of samples.
3. Increasing the number of holes effectively enhances the low-frequency sound absorption coefficients of samples. Also, increasing the adhesive quality and the amount of adhesive required can effectively enhance the low-frequency sound absorption coefficients of samples. These observations provide valuable insights into the factors influencing the sound absorption properties of the materials and suggest potential avenues for optimizing their performance in future applications.

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