ACOUSTIC PERFORMANCE OF A BIO-BASED MULTILAYER WALLPAPER USING HEMP AND STRAW FIBERS

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Abstract

The acoustic behaviour of multilayer wallpaper made from hemp stalk and rice straw is investigated in this study. The work was developed from a broader study on bio-based interior materials, but the present paper focuses on acoustic performance. The proposed wallpaper consists of a porous core layer based on hemp–straw mixtures and a surface layer made of Xuan paper, jute fabric, and dried botanical elements. Samples with different hemp–straw ratios and different thicknesses were prepared under controlled conditions to examine the influence of material composition and specimen thickness on sound absorption. The normal-incidence sound absorption coefficient was measured by means of an impedance tube over the frequency relevant to interior environments such as hotel rooms and bedrooms. The measurements show that the wallpaper provides sound absorption in the speech-frequency range, and that the acoustic response changes with both thickness and fiber composition. The results suggest that bio-based wallpaper can be considered not only as a decorative wall finish, but also as a functional interior layer with acoustic value.

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Keywords: *bio-based materials, acoustic wallpaper, hemp fiber, rice straw, impedance tube*

1. Introduction

In bedrooms and hotel rooms, acoustic comfort is closely tied to how the space is used. Excessive reverberation, audible background noise, and insufficient speech privacy can all affect rest and everyday comfort [1]. For rooms of this kind, relatively short reverberation times are generally preferred [2], [3]. This is also relevant in hotel environments, where acoustic conditions form part of the overall perception of indoor quality [4].

Conventional acoustic solutions are still widely used in buildings, however bio-based alternatives have attracted growing attention in recent years. Recent evaluations on natural fiber sound absorbers and bio-based insulation materials have highlighted their potential to combine acoustic performance with lower environmental impact, but durability, variability, and scalability are still important challenges [5], [6], [13], [14]. Natural fibers and agricultural residues are especially relevant here because their porous and fibrous structure can support sound absorption, often with useful behavior in the mid- and high-frequency range [7], [8], [15].

Among these materials, hemp and straw are a useful combination to explore. Straw-based composites have already been studied as sound-absorbing construction materials [9], [15], while more recent reviews identify hemp fiber as one of the natural fibers with promising acoustic potential [8], [9], [13], [16].

Wallpaper, however, is still discussed far more often as a finish than as an acoustic layer. For that reason, it is worth looking at in acoustic terms. Wallcoverings occupy a large portion of the visible room envelope, and they already need to meet visual, tactile, and practical requirements. The question, then, is whether a wallpaper system can do something more: not replace conventional acoustic products altogether but make a measurable contribution to sound absorption while remaining compatible with interior use.

The present study examines multilayer wallpaper made from hemp stalk and rice straw. The system consists of a porous core layer and a surface layer combining Xuan paper, jute fabric, and dried botanical elements. Samples with different hemp–straw ratios and different thicknesses were prepared under controlled conditions, and their normal-incidence sound absorption coefficient was measured in an impedance tube according to ISO 10534-2 [10]. Attention is given to the frequency range most relevant to hotel rooms and bedrooms, and to the extent to which thickness and fiber composition affect the measured acoustic response.

The contribution of the paper is twofold. First, it examines the acoustic feasibility of wallpaper as a bio-based multilayer absorber. Second, it compares how hemp–straw ratio and thickness affect the response of this thin wallcovering system.

2. Materials and Methods

2.1 Material system and sample preparation

The wallpaper examined in this study was developed as a multilayer bio-based system. Its acoustic core was made from hemp stalk and rice straw bonded with glutinous rice adhesive. This core was combined with a surface layer made of Yunlong bark paper, a handmade type of Chinese Xuan paper produced from paper mulberry bark fibers, together with jute fabric and dried botanical elements. It was chosen because it is light, flexible, and not easily creased, which made it suitable as a support for the botanical surface treatment [11]. A flexible fiber-mesh adhesive tape was used on the back so that the specimen would resemble an interior wallcovering rather than a loose test panel.

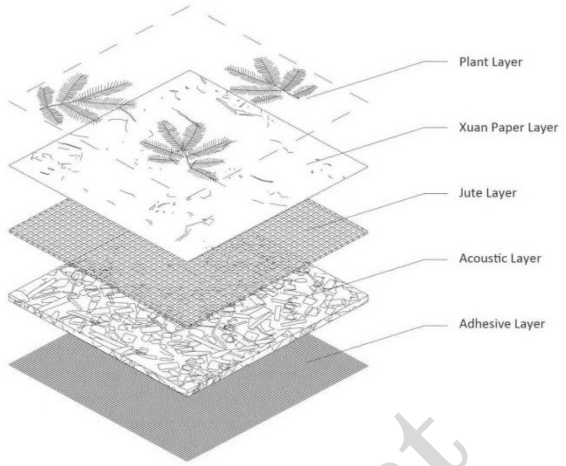

Figure 1. Layered structure of the bio-based acoustic wallpaper. (Source: by authors)

For the acoustic core, rice straw was air-dried and reduced to particles of approximately 5–20 mm in length. Hemp stalk was air-dried, ground, and screened, and only the fraction between 8 and 40 mesh was retained. The adhesive was a handmade glutinous rice starch paste prepared from food-grade glutinous rice flour. Preliminary trials were carried out with powder-to-water mass ratios of 1:5, 1:7, and 1:10, and the 1:7 ratio was selected for the final specimens because it gave the best balance between flowability, bonding, and dimensional stability after drying.

Composite specimens were first formed in a custom circular mold of 10.1 cm diameter to allow for drying shrinkage, then trimmed to a final diameter of 100 mm for impedance tube testing. The hemp–straw mixture and adhesive were placed in the mold and air-dried at room temperature. The surface layer was prepared separately by cutting Yunlong bark paper and jute fabric to the same diameter, bonding them together, and allowing the assembly to air-dry in a ventilated environment for 8–12 h. Dried botanical elements were then attached by hand. After this, the surface layer was laminated to the acoustic core using a thin layer of glutinous rice adhesive, and the bonded specimens were left to cure for at least 12 h before the backing layer was applied.

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Figure 2. Sample not fully dried (left) fully dried and demolded sample (right) (Source: by authors)

Figure 3. (a) Xuan paper from paper mulberry bark; (b) jute fabric; (c) bonded surface and acoustic layers; (d) double-sided tape applied to the back of the sample. (Source: by authors)

2.2 Experimental variables

Two parameters were varied in the sample design: fiber composition and specimen thickness. Fiber composition refers to the mass ratio between hemp stalk and rice straw in the acoustic core. Five ratios were considered: 100/0, 75/25, 50/50, 25/75, and 0/100. Thickness was controlled at three levels, corresponding to wet mold depths of 5, 4, and 3 mm.

To reduce density-related variation across the thickness groups, the total mass of plant fibers and adhesives was adjusted proportionally. For the 5 mm specimens, 3.0 g of dry plant fiber and 25 g of wet adhesive were used. For the 4 mm and 3 mm specimens, these values were reduced to 2.4 g and 20 g, and to 1.8 g and 15 g, respectively. In total, 15 sample conditions were prepared from the combination of five fiber ratios and three thickness levels, and each condition was produced in triplicate. This was intended to reduce, rather than eliminate, density-related variation across samples.

Table 1. Test Sample Variable Configuration Table (Source: by authors)

ID	H:S	Wet t (mm)	Dry t (mm)	m (g)	Dry ρ (g/cm^3)
A1	1:0	5	4.4	6.4	0.185
A2	1:0	4	3.6	4.9	0.173
A3	1:0	3	3	3.9	0.166
B1	3:1	5	4.2	6.9	0.209
B2	3:1	4	3.4	4.6	0.195
B3	3:1	3	2.4	4.3	0.228
C1	1:1	5	4.4	6.4	0.185
C2	1:1	4	3.4	5.2	0.195
C3	1:1	3	2.8	4.1	0.186
D1	1:3	5	3.6	6.4	0.226
D2	1:3	4	3.1	5.5	0.226
D3	1:3	3	2.4	4.5	0.239
E1	0:1	5	3.3	6.2	0.239
E2	0:1	4	2.0	4.8	0.306
E3	0:1	3	1.6	4.1	0.326

H:S = hemp: straw ratio; Wet t = original thickness before drying; Dry t = thickness after drying; Dry m = dry weight; Dry ρ = actual dry-state density.

Figure 4. Prepared specimens for impedance tube testing. (Source: by authors)

2.3 Acoustic measurements

The normal-incidence sound absorption coefficient was measured in an impedance tube using the transfer-function method described in ISO 10534-2. Circular specimens of 100 mm diameter were mounted in a tube

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of the same diameter, with attention paid to edge sealing and sample positioning. Because of the tube size, the analysis focused on the frequency band most relevant to hotel rooms and bedrooms. Measured data were processed in 1/3-octave bands.

Figure 5. Installation of the sample in the impedance tube. (Source: by authors)

Each specimen was measured three times under the same test condition. Repeatability was evaluated automatically in MATLAB using a robust outlier-screening procedure. For each analyzed frequency band, the median response and the median absolute deviation (MAD) were calculated from the repeated curves. A curve was treated as an outlier only when its deviation exceeded a zMAD threshold of 2.5 in at least 50% of the analyzed bands. To avoid over-filtering, at least two curves were always retained. The final curve was then obtained by point-by-point averaging of the remaining measurements. The procedure was fully automated and did not rely on visual screening. A representative example of repeatability is shown for sample C1 in Figure 6.

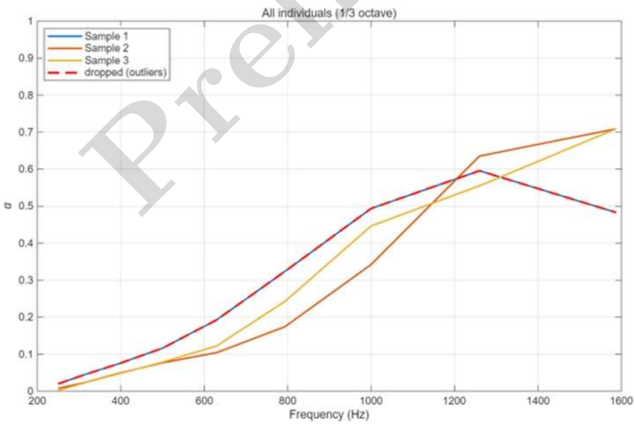

Figure 6. Repeated impedance tube measurements for sample C1. (Source: by authors)

3. Results

The impedance tube measurements showed a clear frequency-dependent pattern for all the sample groups. Sound absorption was low at 250–500 Hz, but it increased as the frequency moved toward the mid- and high-frequency ranges. Across almost all specimens, the main rise occurred between 1000 and 1600 Hz, with peak values consistently appearing at 1600 Hz. This indicates that the multilayer wallpaper behaves primarily as a mid- to high-frequency absorber within the tested range. For this reason, the comparison between specimens was based not only on the full 1/3-octave curves, but also on the values at 250, 500, 1000, and 1600 Hz. To support comparison among the tested configurations, a selected-frequency mean absorption coefficient, denoted as Mean α_{250–1600}, was calculated as the arithmetic mean of the measured absorption coefficients at these four frequencies:

$$\text{Mean } \alpha\ \{250\text{–}1600\} = \frac{\alpha_{250} + \alpha_{500} + \alpha_{1000} + \alpha_{1600}}{4} \quad (1)$$

This value was used only for internal comparison within the present sample set and should not be interpreted as a standardized SAA or NRC rating as defined by ASTM C423 [12].

Figure 7 compares the mean α {250–1600} values of the five hemp–straw ratios, with the variation within each group shown as ±1 standard deviation. The 1:1 group gave the highest average value in the present sample set, while the 0:1 group showed the lowest overall result.

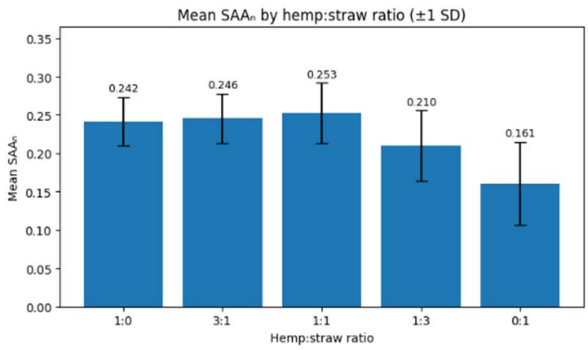

Figure 7. Mean α {250–1600} values by hemp‑straw ratio, with ±1 standard deviation. (Source: by authors)

Thickness also influenced the measured response. Within the same fiber ratio, thicker specimens generally performed better than thinner ones in the 1000–1600 Hz range, while the differences at 250–500 Hz remained limited. This suggests that, within the thickness range tested here, increasing thickness mainly improves mid-

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and high-frequency absorption rather than extending performance toward the low-frequency end.

Among all samples, C1 showed the best overall result. This specimen had a 1:1 hemp–straw ratio and a dry thickness of about 4.4 mm. Its measured values were 0.00 at 250 Hz, 0.08 at 500 Hz, 0.40 at 1000 Hz, and 0.71 at 1600 Hz, giving a mean α value of about 0.298. The peak value was reached at 1600 Hz. The next strongest results were obtained for B2 and A3, but these samples were less balanced at 1000 Hz or more dependent on high-frequency rise. Among the tested configurations, C1 gave the highest mean α value, while the 1:1 group showed the best average performance across the selected frequencies.

Table 2. Measured absorption values and mean α values for all specimens. (Source: by authors)

ID	α250	α500	α1000	α1600	Mean α
A1	0.00	0.08	0.20	0.55	0.208
A2	0.00	0.09	0.21	0.69	0.248
A3	0.00	0.07	0.18	0.83	0.270
B1	0.00	0.09	0.34	0.45	0.220
B2	0.00	0.08	0.20	0.85	0.282
B3	0.00	0.06	0.18	0.70	0.235
C1	0.00	0.08	0.40	0.71	0.298
C2	0.00	0.07	0.31	0.54	0.230
C3	0.01	0.06	0.20	0.65	0.230
D1	0.01	0.08	0.33	0.63	0.262
D2	0.01	0.06	0.24	0.46	0.192
D3	0.01	0.07	0.18	0.44	0.175
E1	0.03	0.06	0.25	0.49	0.208
E2	0.01	0.05	0.21	0.42	0.172
E3	0.00	0.04	0.11	0.26	0.102

α = normal incidence sound absorption coefficient at the indicated frequency; Mean α = Mean α (250–1600), calculated as the arithmetic mean of α250, α500, α1000, and α1600; used only for internal comparison among the tested specimens.

4. Discussion

Because the main increase occurred between 1000 and 1600 Hz, the measured response is more relevant to speech-related indoor reflections than to low-frequency control. Thickness had a visible effect on the response above 1000 Hz, whereas the effect at 250–500 Hz remained limited. Within the range tested here, increasing thickness therefore did not shift the material into low-frequency absorption, but mainly strengthened its behavior in the mid- and high-frequency bands. This is consistent with previous studies on porous natural-fiber materials, which show that thickness and internal structure both affect the measured absorption response, with stronger performance often observed at mid and high frequencies [7], [8], [13], [15].

The influence of fiber ratio appears less linear. The hemp-rich and straw-rich mixtures did not simply perform better as one component increased. Instead, the most balanced response was obtained with the 1:1 mixture. One possible explanation is that this ratio produced a more favorable internal structure, with enough heterogeneity to increase friction and energy dissipation without making the core either too compact or too discontinuous. In the present study, the 1:1 group also gave the most stable combination of values across the selected frequencies, whereas some other groups relied more strongly on a rise at the upper end of the measured band.

The best-performing sample, C1, combined this 1:1 fiber ratio with the largest thickness level in that group. Its strongest response occurred at 1600 Hz, and its overall result remained clearly better than the straw-only samples. This makes it reasonable to see the proposed wallpaper as a material more suited to speech-related and everyday indoor noise than to low-frequency control. For hotel rooms and similar interiors, that is not necessarily a limitation.

The limits of the study should also be noted. The measurements were obtained in an impedance tube under normal incidence, using small circular specimens rather than full wall assemblies. The Mean α value was used only for internal comparison and should not be interpreted as a standardized SAA, NRC, or room-scale absorption rating. Therefore, the measured values should be treated as indicative material-level results rather than direct predictors of full-room performance.

5. Conclusion

This paper examined the acoustic behavior of multilayer wallpaper made from hemp stalk and rice straw. The impedance tube measurements showed that the material acts mainly as a mid- to high-frequency

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absorber within the tested range, with limited absorption at low frequencies. Both fiber composition and thickness influenced the measured response, but the effect of thickness was more evident above 1000 Hz. Among the tested specimens, the 1:1 hemp‑straw mixture gave the most balanced overall performance, and sample C1 showed the best overall response among the tested configurations.

These findings suggest that bio-based wallpaper of this type can contribute to sound absorption in interior spaces, particularly in the frequency range relevant to speech and everyday indoor use. The study does not suggest that such a system can replace all conventional acoustic materials, especially where low-frequency control is required. It does, however, show that wallcoverings can be considered as part of the acoustic design of interior surfaces, and that hemp‑straw multilayer systems merit further investigation.

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