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A Comparative Study: Exploring Diverse Paper-Based Fabrics for Innovative Soundproofing Solutions

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ABSTRACT

The music industry and everyday architecture requires proper soundproofing, with most of the materials used being not sustainable. The utilization of paper fabrics for soundproofing applications has garnered significant attention due to their potential as biodegradable and eco-friendly alternatives in the field of acoustic insulation. This study analyzes three paper fabrics, aerogels, mycelium textiles, and bamboo fibers, and their potential use case in sound insulation and soundproofing. The study compared these fabrics to other non-sustainable materials used in soundproofing and compared different soundproofing measures to prove their efficacy in soundproofing. Despite their sustainability, paper fabrics face limitations for soundproofing due to their short lifespan and higher costs. To enhance their usage, thorough research is needed to improve longevity and performance. Creating foam-like products using paper fabrics, especially bamboo fiber due to its porosity and affordability, could be a strategic approach. Implementing these fabrics as wall-hanging devices instead of building insulation could provide an effective pathway for their sustainable use in soundproofing.

Introduction

With recent concerns surrounding climate change, the need to be resourceful with materials and control waste management is crucial. When observing the music industry, proper sound insulation is needed for recording studios, concert halls, practice rooms, and more. However, soundproofing is not only limited to the music world, but societal architecture such as homes, apartments, and public venues. Furthermore, with loud noises being present in everyday life, occupational hearing loss has become one of the most common work-related illnesses in the United States (Walter & Gürsoy, 2022). Currently, common materials in soundproofing consist of fiberglass, polyester fiber, silicone, and more. Polyester, despite its characteristics of good sound absorption property, has issues of high environmental pollution and high costs (Peng et al., 2015). Fiberglass is shown to be an effective material for sound absorption, with its average sound absorption coefficient of over 0.8 can be achieved in the range of 100-6,400 Hz from a 30 mm fiberglass sample (Sun et al., 2013). However, with fiberglass being a material composed of fine glass fibers embedded in a resin matrix, often made from polyester, epoxy, and other synthetic resins, it is non-biodegradable and can persist in the environment for a long time after its use. Despite the effectiveness of current soundproofing materials, the negative environmental impacts that come from the usage can outweigh the positives of performance when observing the constant construction of buildings and urbanization of society. Therefore, it is essential to find materials to utilize in soundproofing that is both efficient and biodegradable.

Aerogels (nanocellulose)

Aerogels, specifically nanocellulose aerogels, have garnered substantial attention as promising candidates for soundproofing applications, despite challenges associated with production costs. Notably, cellulose nanocrystals (CNC), integral to nanocellulose aerogel, offer a distinct cost advantage compared to other nanoparticles. This section explores the emergence of cellulose aerogels as novel porous sound-absorbing materials, emphasizing their efficiency, recyclability, and degradability (Ruan et al., 2023). A recent study demonstrated the fabrication of multifunctional acoustic absorptive CNC aerogels, employing a green cross-linker, calcium chloride, for CNC cross-linking, followed by freeze-drying (Ruan et al., 2023).

Cellulose nanocrystals (CNC) present distinctive characteristics compared to their native cellulose counterparts. While native cellulose exists as semi-crystalline fibers with morphological variations based on the species and environment of origin, CNC displays heightened strength, low abrasiveness, light weight, and the ability to form hydrogen bonds, facilitating interparticle network formation (Eyley & Thielemans, 2014).

In terms of soundproofing efficacy, CNC aerogels exhibit commendable acoustic absorption performance, displaying attributes such as excellent broadband absorption, good thermal stability, ultralight properties (with a density of 0.036 g/cm^3), and high diffuse reflection characteristics (with an average diffuse reflectance of 98.17% for light). Specific ratings from research articles emphasize the acoustic absorption capabilities of CNC aerogels. These ratings include a high maximum absorption coefficient of 0.99 at 2960 Hz, an average absorption coefficient of 0.85 in the range of 600-6400 Hz, and a broad absorption bandwidth of 4673 Hz with an absorption coefficient exceeding 0.8 (Ruan et al., 2023).

Aerogels, including nanocellulose aerogels, boast high sustainability and environmental friendliness due to inheriting the advantages of cellulose. Furthermore, their broad range of sources enhances their sustainability profile. Manufacturing processes for nanocellulose aerogels encompass different cellulose sources and fabrication methods, which yield varied microstructures and performances (Chen et al., 2021). Generally, these processes involve three main steps: dispersion of nanocellulose, gelation of nanocellulose, and gel drying. The dispersion of nanocellulose is facilitated by the presence of active hydroxyl groups on the nanocellulose surfaces, which enable intermolecular and intramolecular hydrogen bonding, as well as self-aggregation and entanglement of nanocrystals or nanofibrils. Additionally, incorporation of negatively charged groups (such as carboxyl, carboxymethyl, and sulfonic) on nanocellulose surfaces leads to stable and uniform aqueous nanocellulose dispersion, due to electrostatic repulsions between negatively charged nanocellulose and sulfonated CNCs. The subsequent gelation and gel drying processes complete the formation of nanocellulose aerogels.

The natural structure of cellulosic fibers can be explained as a lengthy linear polymer chain made up of repeating units known as β-D-glucopyranose (also called β-1,4-D-anhydro glucopyranose), denoted as C6H11O5. These units are connected through an acetal linkage between carbon atoms C-1 and C-4 in different units, a connection formed by the removal of water. The cellulose chain's ends consist of a reducing end and a nonreducing end. The reducing end features an asymmetrical hemiacetal anomeric carbon atom, while the nonreducing end has a closed-ring structure. Within the cellulose polymer fiber, both amorphous and crystalline domains exist. The mechanical properties are affected by the degrees of polymerization and crystallinity of these domains. Although the fiber offers a blend of low density, high strength, and modulus, these traits heavily rely on the fiber's origin and the methods used for extraction and treatment. Additionally, the mechanical characteristics of the cellulosic fiber are profoundly influenced by the hierarchical arrangement of its amorphous and crystalline components (Ee & Yau Li, 2021). The presence of amorphous and crystalline domains in the cellulose fiber’s structure contributes to the fiber’s ability to absorb and attenuate sound waves. Additionally, higher crystallinity can lead to increased stiffness and strength which can be advantageous in constructing effective soundproofing materials.

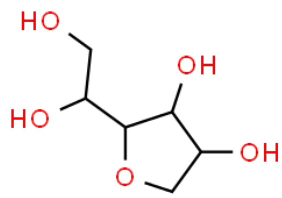

Figure 1. Molecular structure of β-D-glucopyranose. Adapted from "2-(1,2-dihydroxyethyl)-3,4-dihydro-2H-furan-3,4-diol", by ChemSpider. Retrieved from http://www.chemspider.com/Chemical-Structure.10661851.html

The exploration of nanocellulose aerogels as soundproofing materials highlights their unique attributes, from cost considerations to acoustic absorption performance. Their intrinsic environmental sustainability, diverse sources, and intricate manufacturing processes contribute to their potential as innovative and eco-friendly solutions in the realm of acoustic materials.

Mycelium Textiles

Mycelium, the intricate network of thread-like structures produced by fungi, has gained significant attention as a promising material for sustainable textile production. Mycelium textiles offer potential as soundproofing materials, with their effectiveness influenced by the choice of substrates used during their production. Among the substrates suitable for this purpose are rice straw, hemp pith, kenaf fiber, switchgrass, sorghum fiber, cotton bur fiber, and flax shive. Notably, the acoustic absorption performance of mycelium textiles varies according to the substrate employed. For instance, the substrate composed of 100% cotton bur fiber, while performing as the lowest absorber, achieved an acoustic absorption rate exceeding 70% at 1000 Hz (Jones et al., 2018).

The significance of the findings can be further appreciated through a comparison with specific ratings reported in relevant research articles. Utilizing the metrics and measures investigated thus far, these ratings help contextualize the soundproofing capabilities of mycelium textiles. Of particular note is the minimal waste produced during the creation of mycelium-based textiles. These textiles capitalize on the outcomes of fungal growth, as mycelium generates enzymes that facilitate the conversion of substrate biomasses into nutrients. Over time, the decomposition process takes place as plant polymers are gradually replaced by fungal biomass (Jones et al., 2018).

The manufacturing process of mycelium textiles involves three main stages: cultivation of mycelium-based composites, assessment of the cultivated samples' acoustic performance, and cultivation of mycelium-based acoustic panel prototypes. The first stage encompasses the cultivation of mycelium-based composites. This process necessitates the sterilization of prepared substrates within an autoclave chamber to eliminate potential contamination. The cultivated samples subsequently undergo controlled growth in a carefully regulated environment. Initially, they are placed in autoclavable bags for a duration of 12 days, followed by further growth within sterile formworks for an additional 16 days. Furthermore, mycelium mixtures are cultivated in petri dishes specifically designed for sound absorption testing, providing insights into their acoustic performance (Houette et al., 2022).

The physical and mechanical properties of mycelium textiles differ based on the substrate they are cultivated on. This discrepancy ranges from composites having a low density of 60–130 kg/m3 when grown on straw-based substrates, to a greater density of 87–300 kg/m3 when cultivated on sawdust-based substrates (Kaiser et al., 2023). Furthermore, when observing the noise reduction coefficient (NRC) of multiple soundproofing materials, it is seen that low density materials possess higher sound absorption when compared to materials with lower densities. Furthermore, absorption also depends on the construction of product, nature of the material, porosity, and the type of surface alongside density (Nandanwar et al., 2017). When observing the flexibility of mycelium textiles due to its nature of being manipulated during the growth and manufacturing process, it is possible for the material to have large densities that are suitable for soundproofing.

When assessing the acoustic performance of the cultivated samples, it is evident that none of them exhibited high absorption rates within the low-frequency range of 50 Hz to 500 Hz. Nonetheless, fine cardboard samples emerged as the most effective absorbers among the low to mid-frequency range. This result underscores the complex interplay between substrate composition and acoustic characteristics in the development of mycelium-based acoustic panel prototypes. These findings illuminate the potential and limitations of mycelium textiles as soundproofing solutions, paving the way for further refinement and innovation in the realm of sustainable acoustic materials.

Bamboo Fibers

Bamboo fiber is a subject of interest in acoustic material research, raising inquiries about its cost considerations. Bamboo, a composite material comprising plant cells rich in cellulose, hemicellulose, and lignin, has been identified for its potential in sound absorption applications (Pu et al., 2021). Notably, bamboo fiber contains not only these fundamental components but also additional compounds such as phenol, hydrochloric acid, sodium hydroxide, pyridine, acetic anhydride, and gelatin (Pu et al., 2021). To assess the sound absorption performance of this material, a methodology involving the measurement of noise variations between the two sides of the sound-absorbing material was employed, providing insights into the different components of the sound-absorbing mechanism. The frequency range examined spanned from 20 Hz to 14000 Hz. The sound-absorbing characteristics of bamboo fiber were primarily attributed to its pore structure and solid content. Due to its composite nature, bamboo fibers harbor multiple molecular constituents. Consequently, the resonance of sound waves may contribute to heat dispersion, resulting in the consumption of sound energy.

Importantly, the sustainability of bamboo fiber is underscored by its potential for reuse and value addition. Remnants of bamboo maintain the same chemical and physical structure as the original raw materials, enabling their utilization in the production of value-added goods. This cyclic use of bamboo residues further contributes to its environmental viability.

The manufacturing process of bamboo fiber involves several steps. Waste bamboo is initially crushed to yield bamboo shavings of 40-60 mesh size. Subsequently, these shavings undergo a drying process at a consistent temperature of 105°C until a constant weight is achieved (Pu et al., 2021). This procedure contributes to the preparation of bamboo fiber for subsequent applications, emphasizing its potential in sustainable acoustic materials.

Currently, bamboo fiber is being used for a variety of modern applications. In European and Southeast Asian countries, these fibers have experienced rapid growth within the automotive market, with research indicating that economically viable bamboo fiber materials have potential for utilization in automotive components (Kaur et al., 2017). Despite their soundproofing usages not yet being mainstream, bamboo fibers are being used for interior design applications, with various composite formulations utilizing bamboo materials such as roofing, walls, flooring, doors, window frames, stairs, and home decor accents (Kaur et al., 2017).

Bamboo fibers are widely accessible as it is an abundant natural resource in Asia and Middle & South America. It is also known to have extreme strength due to their weight coming from the longitudinal alignment of fibers within their structure (15). The mechanical characteristics of bamboo fibers primarily stem from the cellulose content, which is affected by various factors like the volume fraction of fibers, fiber length, fiber aspect ratio, fiber-matrix adhesion, and fiber orientation. The three different types of bamboo that showed the highest values for bending strength and impact strength are shown to be short fiber bundle, alkali treated filament, and steam exploded filament mixed with polylactic acid (15). Due to bamboo fibers' strength and sturdiness, insulated soundproofing inside walls would be a good use for this material.

Bamboo fiber's composition, sound-absorbing characteristics, and manufacturing process collectively shed light on its potential as an acoustic material. The versatile nature of bamboo, including its molecular constituents and ability to reuse remnants, positions it as a material with promising acoustic and environmental attributes.

Performance Comparison

When contrasting non-paper fabrics with paper fabrics, the most notable distinction lies in their degradability. Below shows a comparative analysis of polyester fibers and fiber glass, two non-sustainable substances commonly used in soundproofing and paper fabrics, mycelium textile, aerogels and bamboo fibers. While materials like polyester fiber and fiberglass can degrade, their decomposition processes often extend over centuries, leading to them being categorized as "non-biodegradable." Conversely, nanocellulose aerogel, mycelium textiles, and bamboo fiber exhibit significantly shorter breakdown periods, positioning them as more environmentally sustainable options over the long term. However, it's worth noting that paper fabrics, despite being biodegradable, tend to have shorter lifespans; for instance, bamboo fiber typically lasts between 3 to 5 years.

Among the investigated paper fabrics, nanocellulose aerogels stand out with a solid lifespan. Nonetheless, their attractiveness is tempered by the substantial costs associated with their production, rendering them less economically viable. When considering cost, lifespan, and degradability collectively, mycelium textiles emerge as a compelling choice due to their reasonable cost, satisfactory lifespan of 20 years, and rapid degradation period of as little as 30 days.

Table 1: Comparative Analysis of Fundamental Characteristics of Biodegradable Paper Fabrics (Aerogels, Mycelium Textiles, Bamboo Fibers) and Non-Biodegradable Soundproofing Materials (Polyester Fiber and Fiberglass)

	Cost per sq-feet	**Lifespan**	**Degradability**
Polyester fiber	\$0.50-\$6.00	20-200 years	not biodegradable
Fiberglass	\$0.88-\$1.64	up to 50 years	not biodegradable
Aerogel (nanocellulose)	\$929	15 years	instantaneous
Mycelium textiles	\$25	20 years	little as 30 days
Bamboo fiber	\$2-\$6	up to 15 years	little as 45 days

When assessing sound absorption capabilities among these materials, both fiberglass and bamboo fiber stand out due to their higher Noise Reduction Coefficient (NRC) values. These elevated NRC values underline their effectiveness in absorbing sound across a broad frequency spectrum. Following closely, aerogel (nanocellulose) demonstrates commendable sound absorption properties with an NRC of 0.88. In contrast, although polyester fiber possesses moderate sound absorption capacity with an NRC range of 0.8-1, it falls short of the superior performance of fiberglass and bamboo fiber. Mycelium textiles present the lowest NRC value of 0.64, indicating comparatively weaker sound absorption efficiency.

Shifting the focus to sound reflection, fiberglass takes the lead by effectively minimizing sound reflection, evident from its lower Sound Reflection Index (SRI) range of 0.9-0.95. In contrast, polyester fiber demonstrates a somewhat higher SRI of 0.79, suggesting a tendency to reflect sound. Unfortunately, SRI information is unavailable for aerogel (nanocellulose), mycelium textiles, and bamboo fiber.

The materials' capacity to regulate sound transmission through walls, as indicated by their Sound Transmission Class (STC) ratings, offers valuable insights. In this regard, fiberglass shines with an impressive STC of 39, highlighting its efficacy in blocking sound transmission. Aerogel (nanocellulose) also demonstrates moderate STC values of 35, aligning with its balanced attributes of sound absorption and transmission control. However, bamboo fiber shows relatively lower STC values, implying potential limitations in managing sound transmission through walls.

Table 2: Comparative Analysis of Soundproofing Metrics for Biodegradable Paper Fabrics and Non-Biodegradable Soundproofing Materials

	NRC	SRI	STC
Polyester fiber	0.8-1	0.79	N/A
Fiberglass	0.9-0.95	0.9-0.95	39
Aerogel (nanocellulose)	0.88	0.81	35
Mycelium textiles	0.64	N/A	32
Bamboo fiber	0.95 (above 3kHz)	N/A	9-14

Fiberglass emerges as a versatile choice excelling in both sound absorption and transmission control, making it particularly suitable for environments requiring comprehensive noise reduction and precise acoustic management. Bamboo fiber, with its impressive sound absorption capacity in higher frequencies, proves advantageous for specific applications like music practice rooms. Nanocellulose aerogels, especially when integrated with paper fabric, present a well-rounded solution encompassing both sound absorption and transmission control attributes. Polyester fiber offers moderate sound absorption capabilities but falls short of the superior performance of some alternatives. Lastly, while mycelium textiles might not lead in sound absorption, their appeal lies in their distinctive sustainable and aesthetic advantages. Ultimately, material selection should align with the acoustic needs and design intentions of the specific space in consideration.

Conclusion

Despite the sustainable appeal from paper fabrics, there are limitations that keep them from being widely used for sound proofing. The largest drawback is the lifespan, with textiles such as bamboo fiber only lasting for 3-5 years. Furthermore, certain paper fabrics, such as mycelium textiles, last for up to 20 years but have costs that can be seen as over the top. When deciding what materials to use for soundproofing, although the performance is crucial, availability can be seen as more vital in certain situations, deeming paper fabrics to be difficult to utilize due to their senescence and higher costs.

In order for paper fabrics to be regularly used materials in the soundproofing industry, the general lifespans and overall performance should be better researched and engineered in order to outperform the current unsustainable materials being used currently. Utilizing the disadvantages of paper fabrics, the best way to introduce these textiles into the soundproofing industry would be to use the materials to create a product that works similarly to soundproofing foams. Foams with high porosity offer notable benefits, including their low density, expansive surface area, and cost-effective manufacturing (Zarek, 1978). An ideal paper fabric for soundproofing foams would be bamboo fiber. Bamboo fibers have a porosity of 73.6% and are an affordable variation of paper fabrics, rendering them the most suitable for foam soundproofing (Tanpichai et al., 2019). Due to the low lifespans, rather than using the paper fabrics as soundproofing insulation for buildings and walls, having a device that can be hung on walls can be a fitting introduction for using sustainable textiles.

Beyond its role in the soundproofing industry, paper fabrics have achieved success in diverse domains, including packaging. The extensive use of petroleum-derived polymers across various applications has encountered challenges related to limited resources, escalating expenses, and persistent environmental impact, prompting the exploration of sustainable alternatives (Nurul Fazita et al., 2016). One such solution emerges through green composites, denoting biodegradable polymers reinforced with natural fibers, providing an eco-conscious alternative to conventional petroleum-based counterparts (Nurul Fazita et al., 2016). Notably, poly(lactic) acid (PLA), a biodegradable polymer sourced from renewable materials, has emerged as a compelling option for packaging due to its transparency, mechanical prowess, and environmentally friendly degradation (Nurul Fazita et al., 2016). Recent research endeavors have investigated the integration of natural fabric-based reinforcements, like bamboo fabric, aiming to enhance the stiffness, strength, impact resistance, and heat deflection temperature of PLA composites (Nurul Fazita et al., 2016). Paramount attributes for packaging applications encompass physical properties, heat deflection temperature, impact resistance, recyclability, and biodegradability (Nurul Fazita et al., 2016). In this context, bamboo fabric-based biocomposites introduce a distinctive approach compared to conventional short fiber-based composites, potentially ushering in more effective and efficient packaging materials.

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