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SUSTAINABLE ACOUSTIC MATERIALS FROM PLANT-BASED AND AQUATIC BIOMASS: A REVIEW

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Abstract. This literature review focuses on the potential of land and aquatic plants to improve acoustic comfort in indoor environments as a substitute for synthetic materials. Plant-based acoustic materials could be used to improve acoustic parameters for environments like offices and educational buildings, where acoustic comfort is crucial for concentration, productivity, and overall well-being. High reverberation time in these settings can cause stress, reduce cognitive performance, and increase general discomfort. Terrestrial and aquatic plant-based have drawn a lot of interest as materials that are sustainable solution to this problem. This review examines the potential of both land-grown plant fibres (e.g., kapok, hemp, flax) and aquatic biomass (reeds, cattails, algae) for sound absorption applications. Compared to terrestrial plant fibres, aquatic biomass has the advantage of reducing eutrophication ecological risk in water bodies. Various properties that affect the sound-absorbing capabilities of the materials are discussed. Overall, using plant-based and aquatic biomass fibres for sustainable acoustic materials provides environmental benefits, but highlights the need for design strategies to maximize their application in buildings.

Keywords: acoustic comfort, sound absorption, plant-based fibres, algae.

1. Introduction

People spend an average of 90% of their time in enclosed buildings, which increases their exposure to indoor environmental conditions (Klepeis et al., 2001; Kristiansen et al., 2011). As a result, the quality of indoor environments' acoustic conditions plays a crucial role in daily comfort, health, and performance.

Long reverberation times can degrade the ability of a listener to discriminate useful sounds (e.g., target voices) in everyday life environments. These effects are particularly critical in school settings, where both teaching and learning activities rely heavily on effective speech communication. Detrimental effects are especially strong in those environments, as they negatively affect speaking, listening and cognitive capability (Liu et al., 2023; Yahya et al., 2019).

A good acoustic environment is also important in offices. The Stress Research Institute and the Department of Psychology, Stockholm University, found that environments with improved sound quality were beneficial for work performance and general health. Improved sound quality in offices causes less cognitive stress and less disturbance (Beldam, 2019; Seddigh et al., 2015).

These research findings emphasize the effect of room acoustic properties on studying, teaching and office work quality and demonstrate that investing in room acoustic comfort improvement can result in measurable benefits across education, healthcare, and other environments, even when improved beyond mere regulatory compliance.

To improve room acoustic comfort, sound absorbing materials are used. However, these sound absorbing materials are predominantly manufactured using synthetic materials (Bonga et al., 2024). Production of these synthetic materials is environmentally unsustainable, as they are not biodegradable and generate substantial emissions of carbon dioxide. As a result, increasing attention has been directed toward the development of green acoustic absorber materials based on natural plant-based fibres, given that they are biodegradable and have a lower environmental impact throughout the manufacturing process (Yahya et al., 2019). Most commonly, regular land-grown plant-based fibres are used to produce sustainable absorbers. However, water body eutrophication, caused by extensive nitrogen and phosphorus influx in water bodies, is becoming an increasingly severe global problem. This increased flow of nutrients increases the

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growth of macrophytes (such as reeds and cattails) and also increases algae growth in water bodies (Dubey & Dutta, 2019; Khan & Mohammad, 2014). Such biomass can be manufactured into sustainable sound-absorbing materials, simultaneously contributing to acoustic material development and to the mitigation of eutrophication-related environmental impacts. The aim of this article is to review the current applications of plant-based fibres across various industries, with particular emphasis on their use in acoustic materials and their sound absorption performance, to identify existing knowledge gaps in the use of these fibres, and to suggest optimisation approaches for these under-investigated fibres in future studies.

2. A review of plant-based fibre current applications and their sound absorption capabilities

Some natural fibres such as bamboo fibre, luffa fibre, date palm fibre, fique fibre, coir fibre, kenaf, hemp and cane fibre have poor spinnability and can't be used in textiles, so they were extensively researched for potential in acoustic absorption applications (Tang & Yan, 2017).

Plant fibres have a porous and hollow lumen structure, which greatly contribute to their sound absorption capabilities. The presence of pores allows sound waves to dissipate energy as they pass through the material, effectively reducing noise levels (Sambandamoorthy et al., 2020). Plant fibres can be classified depending on the part of the plant that was used to produce the fibres. The most common classes are seed, bast, wood and straw (Karaduman, 2023; Mohanty et al., 2005).

2.1. Seed fibres

Plant seed fibres are being utilised to create biodegradable packaging materials, which are essential in reducing plastic waste (Yildiz & Öztekin, 2024). Blending poplar seed hair fibres with PET in needle-punched nonwovens significantly improves oil absorption and dye removal, demonstrating their potential as sustainable high-performance textile materials and for wastewater treatment (Usta et al., 2024). These fibres show how natural materials can serve as sustainable substitutes for synthetic ones across a wide range of applications.

Kapok, poplar, and cotton are the main seed fibres utilised in acoustic applications. These fibres are lightweight and highly porous. Because of its natural hollow structure, kapok fibre has excellent acoustical damping performance, making it effective for sound absorption and noise reduction in various acoustic materials (Xiang et al., 2013; Liu et al., 2020).

All three seed fibres show low sound absorption at lower frequencies (up to 1000 Hz). Kapok and poplar seed fibres exhibit a rapid increase in sound absorption at frequencies above 1000 Hz, being significantly superior to cotton at frequencies up to 3150 Hz. At frequencies above 3150 Hz, the sound absorption coefficient (α) of kapok and poplar fibres remains around 0.8, while cotton shows superior sound absorption at very high frequencies (5000–6000 Hz), where α approaches near-perfect absorption of 1.0 (Liu et al., 2020). However, the average sound absorption coefficient of cotton fibres across all frequencies remains the lowest of these seed fibres.

2.2. Bast fibres

Bast fibres are part of the plant that are extracted from the outer stem layer. Bast fibres mechanically support the phloem (Guerriero et al., 2017; Summerscales et al., 2010). Crops like hemp, flax and kenaf are main sources for bast fibres (see Figure 1) that are used in many industries, contributing to a sustainable economy, for instance, clothing textiles, industrial textiles, paper materials and biocomposites in structural applications (Deyholos & Potter, 2013; Saleem et al., 2020; Yu et al., 2019).

Figure 1. Commonly used bast fibers: a) hemp plant; b) hemp fibre; c) flax plant; d) flax fibre

Hemp is a sustainable material that grows rapidly and produces high biomass yields (up to 12 tonnes of dry raw material per hectare). Hemp growth suppresses weeds, so it requires no herbicides or insecticides. Hemp fibres can serve as ideal alternatives to synthetic materials like glass fibre (Arnaud & Gourlay, 2011; Gumanová et al., 2022; Yang et al., 2020). Strazdas and Januševičius (2024) demonstrated that all types of hemp fibres exhibit excellent sound absorption performance at medium (600–2000 Hz) and high (2500–5000 Hz) frequencies, with sound absorption coefficients reaching up to 0.99 (Strazdas & Januševičius, 2024). Gumanová et al. (2022) observed similar results.

Flax fibre is obtained from the plant *Linum usitatissimum*, which has traditionally been used in textiles for the production of durable linen fabrics (Baley et al., 2018). Flax fibre is also increasingly used as an environmentally friendly reinforcing material in polymer composites. These composites are applied in various industries, including the automotive, aerospace, marine, and construction sectors, because of their high specific strength and stiffness (Das et al., 2022).

Kenaf is a natural fibre obtained from *Hibiscus cannabinus*. Kenaf belongs to the Malvaceae family, which is the same plant family as cotton (Lim et al., 2017). Kenaf has been recognised as an essential fibre source for composite material in various industrial applications because its bast fibres are inexpensive, durable, recyclable, and biodegradable (Saad & Kamal, 2012; Xue et al., 2007).

However, all three bast fibres show low sound absorption coeficcients in frequencies below 800 Hz, where absorption coefficients do not reach 0.5 (Ramam et al., 2024).

2.3. Wood fibre

Wood fibre and other cellulose-based materials are utilised to develop biodegradable packaging, aiming to reduce dependence on petroleum-based plastic packaging (Mondal et al., 2025; Rashid et al., 2025). The fashion industry is also increasingly exploring wood-based fibres as sustainable alternatives; these fibres can be used alone or blended with other materials to create innovative textiles (Wallius & Näyhä, 2025).

Wood's properties, especially its porosity, have an important role in sound absorption. Even though woods with higher gas permeability and larger pore sizes (for example, oak and hackberry) tend to perform better in sound absorption at lower frequencies, study done by Kolya and Kang (2025), proves that wood performs poorly in sound absorption context, across all frequencies in the 250–6000 Hz range. In this frequency range sample do not reach sound absorption coefficient above 0.5. However, wood SAC in 250–500 Hz range greatly increases when air gap is introduced, reaching up to 0.9 with 40 mm air gap (it is also noticeable that air gap increases from 30 mm to 40 provides little to none improvement). Because of poor sound absorption as a plain material, in acoustics wood fibres are usually used in composites, for example to produce perforated acoustic panels (Dong et al., 2017).

2.4. A review of water plants' and algae's current applications and their sound absorption capabilities

Aquatic plants such as reeds (Phragmites australis) and cattails (Typha spp.) and algae, which are promoted by eutrophication, pose a threat to ecosystems due to their excessively rapid spread. This invasion is particularly harmful in lakes with threatened species and communities, as it results in the decline of many important aquatic species (Foggi et al., 2011). This excessive biomass can be utilised as natural fibres for the sustainable production of acoustic materials. In addition to sustainable acoustic materials, production plants also absorb excess nutrients and pollutants from water, and removing them could improve water quality and overall ecosystem health (Berry et al., 2017).

2.5. Reeds and cattails

Reeds have been investigated as a potential alternative fibre source for the paper industry. However, their high extractive and silica content causes difficulties in the manufacturing process (Wille et al., 2017). Reeds such as *Schoenoplectus californicus* exhibit a high capacity to absorb heavy metals, including copper, pesticides, and excess nutrients from water, making them suitable for the treatment of polluted, including eutrophicated, waters (Miglioranza et al., 2004; Murray Gulde et al., 2005).

There are currently limited studies investigating the sound absorption properties of reeds and cattail, highlighting a gap in existing research. Traditional acoustic absorbers for low frequencies typically require larger volumes; however, recent studies indicate that reeds exhibit significant sound absorption at frequencies below 1000 Hz while occupying very little space. This phenomenon remains poorly understood and has led to new interests in understanding this acoustic behaviour, as other natural fibres usually have great SAC only in medium to high frequency (>800 Hz) (Asdrubali et al., 2015; Lepak et al., 2018). Similarly,

Algae are rapidly growing aquatic organisms whose biomass increases in eutrophicated water bodies, particularly due to the rising availability of nutrients. Algae have commonly been perceived as an ecological issue but their structural and mechanical properties can be adapted for applications in acoustics.

Research done by Astrauskas et al. (2023) has confirmed that dried algae could be used as an efficient material for sound absorption applications. In study different types of algae (red, brown, and green) and their mixtures were tested for their sound absorption properties. The sound absorption coefficient varied with varying density of the measured algae samples (from 50 to 150 kg/m^3 with 25 kg/m^3 increments). With higher density samples performing better in frequencies below 1000 Hz. Most tested algae samples of higher density (>100 kg/m^3) resulted in good sound absorption ($\alpha > 0.5$) in 315–1000 Hz frequency range, which is not usually observed in plant-based fibers. The highest absorption observed in a mixture of brown and red algae at a density of 100 kg/m^3. The peak sound absorption coefficient reached 0.98 at 1000 Hz for a mixture of green and red algae at a density of 75 kg/m^3. Even though there are not many studies on the measurement of the sound absorption coefficient (SAC) for algae, current research suggests that algae perform better at lower frequencies compared to plant-based fibres, making them a promising area of research for sound absorption applications.

Furthermore, binders utilized for algae-based acoustic panels are not thoroughly explored. Studies carried out to assess the effect of the binders on the manufacturing processes and the durability of the panels are limited. Further studies are required to evaluate algae-based sound absorbing materials manufacturing processes, binder selection, and long-term durability, including fire and humidity resistance and biodegradation. Summary of currently most widely used plant-based fibres classes and their sound absorption potential is provided in Table 1.

Table 1. Plant-based fibre type and sound absorption potential

Fibre class	Sound absorption potential
Seed	Low sound absorption (α < 0.5) in frequencies below 1000 Hz, high sound absorption (α > 0.5) in frequencies above 1000 Hz (except for cotton, which perform poorly up to 2000 Hz); in frequencies above 4000 Hz cotton performs the best, achieving up to 1.0 sound absorption coefficient
Bast	Low SAC (α < 0.5) in frequencies below 800 Hz; excellent SAC (α up to 0.99) in frequencies above 2000 Hz
Wood	Low SAC (α < 0.5) in all 250–6000 Hz frequency range; usually used as a layer in composite perforated acoustic panels with air gap – air gap increases SAC up to 0.9 (depending on wood type)
Reed and cattails	Knowledge gap; good SAC in frequencies below 1000 Hz, unlike most natural fibers, but this behavior is not well understood
Algae	Knowledge gap; good SAC (α > 0.5) in 315–1000 Hz frequency range for samples of >100 kg/m^3 density; high SAC (α > 0.75) in 1000–5000 Hz frequency range

Reeds and cattails exhibit promising sound absorption below 1000 Hz, unlike most natural fibers, but their behavior is not well understood, highlighting a clear knowledge gap. Algae demonstrate good sound absorption in 315–1000 Hz frequency range and high sound absorption in 1000–5000 Hz frequency range. SAC range shift is related to sample density, especially in lower frequencies. However, research on reeds, cattails and especially on algae properties, manufacturing, and long-term durability is still limited.

3. Engineering solutions for water plants and algae fibres sound absorption optimization

The acoustic performance of fibrous and porous materials can be assessed using various methods. The sound absorption coefficient is commonly measured using three main testing methods: the reverberation chamber method and the impedance tube method. Using a standing wave (also referred to as impedance) tube to characterise the materials and calculate the sound absorption coefficient is one of the most popular methods (International Organization for Standardization, 1996, 1998; Liu et al., 2025).

The main fibrous materials parameters that influence the acoustic absorption coefficient are porosity, thickness, and pore size (Tang & Yan, 2017). To increase the sound absorption of materials, these parameters can be modified using physical methods, such as changing their density and product thickness, as well as multilayering materials and introducing perforation.

3.1. The role of material thickness, density and air flow resistivity

Sample thickness. Generally, sound absorption coefficient increases as material thickness increases. This relationship is more distinct for mid frequencies (800–2500 Hz) than for high frequencies. This is because thicker materials can better dampen the longer wavelengths of lower frequencies (Fu et al., 2020; Su et al., 2011).

In the studies done with bagasse fibres (see Figure 2), the sound absorption coefficient was found to be significantly better with higher-thickness material. A maximum sound absorption coefficient of 0.75 is found for the 30 mm thickness sample. The most significant difference is observed in medium frequencies (800–2500 Hz); the sound absorption coefficient of the 30 mm thickness sample compared to the 10 mm thickness sample peaked at 2500 Hz, where it is 2.4 times higher (Malawade & Jadhav, 2019). This means thickness has significant importance in improving material sound absorption.

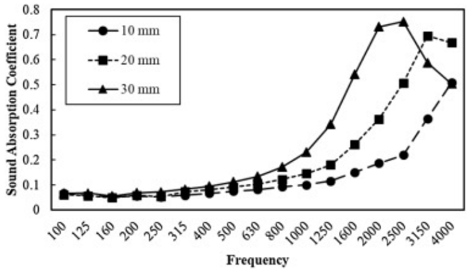

Figure 2. Sound absorption coefficient of different thickness of bagasse fibres (source: Malawade & Jadhav, 2019)

Similar trends are observed with kapok, hemp, coconut fibre and other plant-based fibres (Jang, 2023; Lyu et al., 2021; Strazdas & Januševičius, 2024; Zulkifli et al., 2010).

Sample density. Similarly, to sample thickness, increasing the density of natural fibre samples improves their sound absorption (Rusli et al., 2019; Sekar et al., 2021). However, unlike the effect of thickness, where the absorption coefficient improves at lower frequencies, for the increasing bulk density, the improvement is obvious from the low to high frequency range (Lim et al., 2017). This is caused by the increased resistance to airflow and the enhanced interaction between sound waves and the material structure (Su et al., 2011). The greater the density, the greater the energy lost caused by the improvement of the complexity of the sound path (tortuosity) in the absorbing material (Lim et al., 2017).

Even though increasing sample density increases sound absorption, a reversed trend is expected when the fibres are too densely packed . In the case of kenaf fibres (see Figure 3), it can be observed that the absorption performance started to drop after 1.75 kHz for samples with a bulk density of 160 kg/m³, which means that this density is optimal for the highest SAC.

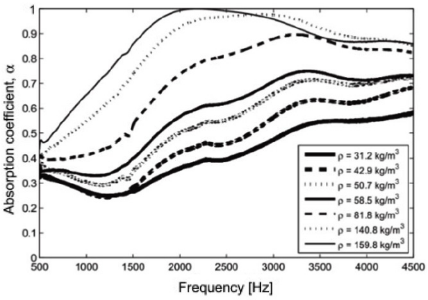

Figure 3. Absorption coefficient of kenaf fibre with identical thicknesses of 30 mm and varying bulk densities (source: Lim et al., 2017)

Similar trend is also highlighted in studies where sound absorption coefficients of oil palm empty fruit bunch fibres samples with different densities at a fixed thickness of 10 mm were measured (see Figure 4). As density increases, sound absorption improves, reaching its peak performance at 468 kg/m³. However, excessively high densities (702 and 818 kg/m³) limit sound absorption to below 0.5 across all frequencies. Similarly, the low-density sample (117 kg/m³) also shows poor sound absorption.

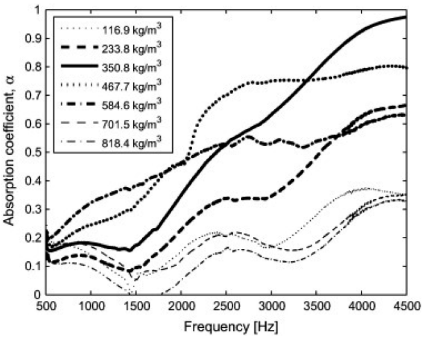

Figure 4. Sound absorption coefficient of 10 mm thickness oil palm empty fruit bunch fibres samples with different densities (source: Or et al., 2016)

Flow resistivity is an important parameter in determining the sound absorption properties of acoustic panels. It measures the resistance to airflow through a porous material and directly influences the material's ability to absorb sound (Rodríguez et al., 2022).

A density that is too high can reduce the porosity of a sample and significantly increase its flow resistivity. This makes it difficult for sound waves to penetrate a material, reducing its absorption performance (Istana et al., 2023).

For water plants and algae fibres, because of their porous structure and low natural density, both density and thickness are important parameters for optimising material sound absorption. Adjusting the produced material's bulk density to an optimal level is essential: too low a density could result in insufficient tortuosity and poor energy dissipation across the sample, while too dense fibres reduce airflow and acoustic performance. Similarly, increasing material thickness enhances airflow resistivity and energy dissipation, in this way improving absorption at mid and lower frequencies. To achieve the most efficient acoustic performance from water plants and algae, both optimal sample density and thickness must be carefully considered in the design stage.

3.2. Engineering solutions for further acoustic potential improvement for water plants and algae fibres

3.2.1. Air gap

Even though increased sample thickness and density increase sound absorption and shift it to lower frequencies, at lower frequencies SAC stays relatively low. To address this problem, different thickness air gaps behind samples can be introduced.

Introducing an air gap behind a sound-absorbing material causes sound energy that passes through the material without being absorbed or converted into heat to encounter additional resistance in the air. This additional energy reduction happens through a mechanism known as the Helmholtz resonance effect. This effect can amplify certain sound frequencies, causing them to oscillate with greater intensity. As the sound energy reaches its peak, it is gradually weakened by friction between the sound waves and air particles, which converts the sound energy into heat (Muhammad et al., 2012; Norton & Karczub, 2003; Zhang et al., 2012).

Introducing an air gap not only increases SAC but also reduces material costs by partially replacing fibrous materials with air cavities (see Figure 5).

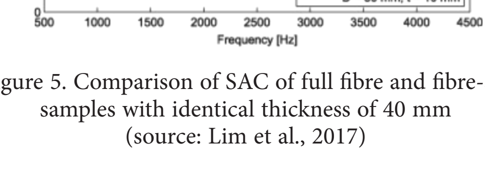

Figure 5. Comparison of SAC of full fibre and fibre-air samples with identical thickness of 40 mm
(source: Lim et al., 2017)

By introducing an air gap in the absorber system, usage of kenaf fibres can be reduced by 25% while sustaining a similar SAC as full fibre samples.

SAC improvements are consistently observed across different studies; however, optimal air gap thickness varies depending on the material type, thickness and desired frequency for sound absorption (Mohammadi et al., 2024; Mvubu et al., 2019). Moreover, increasing the air gap above a certain thickness is unreasonable. For thicker samples (>50 mm thickness), application of an air gap resulted in minor or no improvement at all (Putra et al., 2018).

This makes air gaps a valuable design consideration for developing effective water plants and algae fibre-based acoustic materials.

3.2.2. Multi-layering

Creating composite materials from multiple layers combines unique properties of different materials. Viscous, thermal, and structural losses in multilayered material expand sound absorption to a wider frequency range.

Combining coir and kenaf fibres, with kenaf in the front layer, significantly improves SAC at higher frequencies. In the study done by Kassim et al. (2023), a 2 mm kapok plate was used with coir fibres to achieve a total of 22 mm sample thickness by varying the layers' position in the sample and the total thickness of coir fibres Results are presented in Figure 6.

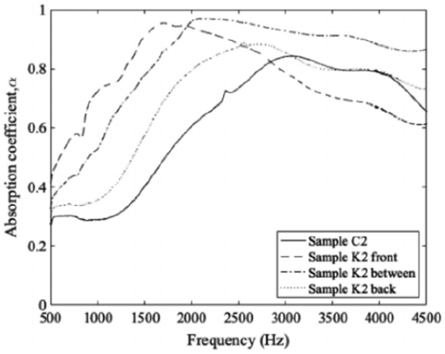

Figure 6. Sound absorption performance of coir sample with varied kapok positions (source: Kassim et al., 2023)

In this case kapok placed between coir layers experiences sound energy twice – once when sound waves are transmitted and once when they are reflected. This mechanism enhances sound absorption, especially at high frequencies (above 2000 Hz). In contrast, kapok positioned in front of the coir layer absorbs more lower-frequency sound (500–2000 Hz) due to the thicker continuous coir fibre layer.

Similar strategies can be applied to water plants and algae fibres. By creating multilayer composites with different water plant or algae fibre thicknesses and densities, it is possible to maximise their acoustic potential.

3.2.3. Micro-perforated facing

Enhancing sound absorption in low frequencies requires thick porous material. According to the λ/4 rule (where λ is the wavelength of a sound at a specific frequency), a porous absorber performs best when its thickness is one-quarter of the sound wavelength (Cox & D'Antonio, 2016; Van Damme et al., 2024). For instance, at a frequency of 250 Hz, for optimal performance an absorber should be approximately 34.3 cm thick, which is both economically and spatially unreasonable.

To address this problem and enhance absorption at lower frequencies, researchers have focused on the utilisation of micro-perforated panels (MPP).

MPP consists of a solid plate that has a number of sub-millimetre-diameter holes drilled into it. The mechanism by which the MPP absorbs sound depends mainly upon the transmission of sound waves through these small holes – sound travels through these openings, resulting in viscous losses that convert sounds to heat.

In MPP resonant frequency and broadband frequency absorption can be regulated by hole diameter, perforation percentage, and absorber thickness behind MPPs (Hashemi et al., 2022).

Hole diameter mostly affects low-frequency sound absorption. Larger hole diameters tend to enhance absorption at lower frequencies because larger holes allow more sound waves to interact with the panel's internal structure, leading to better absorption in this frequency range (Tang & Cheng, 2025). Distance between holes also have to be considered. When the distance between holes is less than twice their diameter, interactions between neighbouring holes modify the flow field and shear region and influence absorption performance. Adjusting the distance-to-diameter ratio can therefore optimise sound absorption (Tayong et al., 2011).

Increasing the perforating rate causes the panel's resonance to shift toward higher frequencies (see Figure 7). On the contrary, if the perforation ratio is decreased, the resonance shifts to the lower frequency range. It is important to note that the perforation ratio has an impact on the bandwidth rather than the amplitude (JavadSheikhMozafari, 2024).

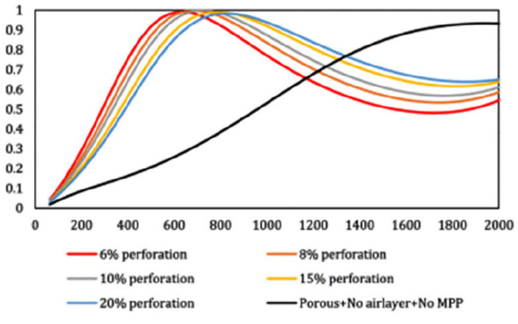

Figure 7. The influence of the MPP perforation ratio on the overall performance of the composite (source: JavadSheikhMozafari, 2024)

The MPP layer contributes acoustic mass reactance, which counteracts the acoustic stiffness reactance of the porous material placed in front of a rigid backing at the frequency of peak sound absorption. Increasing the perforation ratio reduces the total acoustic mass of the sample and raises the resonant frequency at which the maximum sound absorption occurs. To achieve a desired peak absorption frequency, the perforation ratio of the MPP layer or the thickness of the porous material must be appropriately adjusted in order with backing porous materials (Liu et al., 2017).

If MPP wall thickness is increased, sound absorption at middle-high frequency bands continues to increase, but the high-frequency band starts to decrease (Fu et al., 2020).

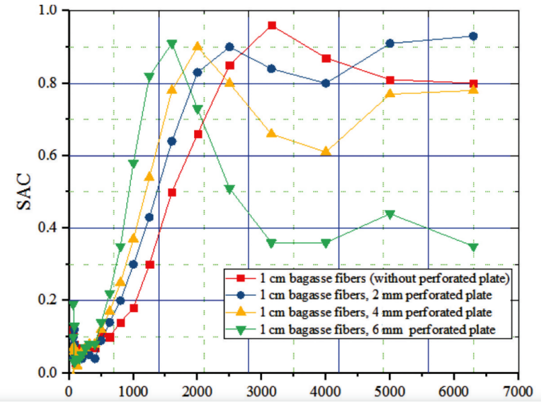

Figure 8. Perforated plate thickness effect on bagasse fibres sound absorption (source: Beheshti et al., 2021)

Beheshti et al. (2021) found that as the thickness of the MPP increases, the SAC increases at low frequencies. However, the use of thick micro-perforated panels backed by a porous absorbent layer is not recommended for controlling sounds with a frequencies higher than 3000 Hz (see Figure 8).

4. Discussion and implementation challenges

4.1. Discussion

Density greatly influences SAC. As excessive compaction reduces porosity and restricts sound penetration, decreasing absorption, it is especially relevant for water plants and algae fibres, whose low natural density requires careful adjustment to maximise energy dissipation without over-compacting the material.

The introduction of air gaps to improve sound absorption is especially advantageous for water plants and algae, as it improves low-frequency absorption and reduces biomass consumption. This is important since these fibres are extracted as waste of eutrophication, the biomass amount can be limited in some cases.

Multilayer setups show how important structural design is in frequency-dependent absorption. Performance depends on how the layers are arranged, not just on the materials used. For water plants and algae fibres, mixing layers with different densities, thicknesses, or species can improve broadband absorption by using complementary loss mechanisms.

Using very thick porous material does not have optimal performance at lower frequencies. To address this, adopting composite panels with reduced porous layer thickness, along with the implementation of an MPP layer and air layer, proved to be a more efficient solution. This strategy not only enhanced performance but also minimised costs and spatial requirements (Hashemi et al., 2022).

However, with these developments in plant-based fibre acoustic properties there are still several areas of uncertainty. The unexplained low frequency sound absorption behaviour of the reeds may be due to the presence of resonant vibrational modes in there structure or anisotropic pore networks that are present in most submerged plants. The role of binder, sensitivity to moisture and the mechanical stability and long-term durability is not well studied for materials based on algae. This limits direct comparison with existing synthetic absorbers.

4.2. Implementation challenges

Plant fibres absorb moisture, which can cause them to break down and perform worse over time (Das et al., 2025). Also, there is often poor interfacial adhesion between hydrophilic plant fibres and hydrophobic polymers used in composites. This incompatibility can lead to weak bonding and reduced overall performance of the acoustic panels (Ndazi et al., 2006).

Plant fibres generally have lower mechanical properties compared to synthetic fibres. This includes lower tensile strength and impact resistance (Akter et al., 2023). Furthermore, the variability in fibre quality and mechanical properties also poses a challenge for consistent performance (Akter et al., 2023; Pater et al., 2025).

Seasonal and environmental factors can cause significant fluctuations in the biomass of algae and aquatic plants. This variability might lead to inconsistent performance in sound absorption (Yoshioka et al., 2025).

Algae and aquatic plants break down over time, which can release different volatile organic sulphur compounds like hydrogen sulphide, dimethyl sulphide, and dimethyl trisulphide. These compounds can cause the unpleasant odour in the room (Shuyun et al., 2016; Wang et al., 2023). Decomposition can also weaken the structure and sound performance of the panels, increasing the need for regular maintenance or replacement.

These challenges could potentially be mitigated by incorporating suitable binders, which may enhance mechanical stability, moisture resistance, and overall durability of plant-based and aquatic fibre acoustic materials.

5. Conclusions

1. Plant-based materials can be implemented as effective sustainable sound absorbers. For example seed, bast, and wood fibres exhibit good sound absorption, especially at higher frequencie. These fibres have the potential of replacing synthetic materials in acoustics applications. But niches of aquatic plants and algae have not been thoroughly studied yet to require further investigation.

2. Non-acoustic parameters (thickness, density, porosity) of plant-based fibres significantly affect the sound absorption coefficient. Optimal design of these parameters in water plants and algae based acoustic materials could be essential improvement for sound absorption, especially for algae fibres which exibit low natural density.

3. Engineering strategies such as introducing air gaps, multi-layering, and using micro-perforated panels can significantly enhance sound absorption, particularly at low frequencies, while reducing material usage and production costs. These approaches are especially promising for underexplored biomasses like reeds, cattails, and algae. Reeds and cattails already exhibit good absorption below 1000 Hz, and incorporating them into layered or micro-perforated composite panels with air gaps could further improve their acoustic performance and consistency. Similarly, algae, which show high absorption across both 315–1000 Hz and 1000–5000 Hz for higher-density samples, could benefit from engineering designs that optimize panel thickness, layering, or perforation patterns, enabling more efficient use of biomass while tailoring absorption to specific frequency ranges.

4. Plant-based and aquatic fibres face usage limitations, including moisture sensitivity, decomposition, variable mechanical properties that depend on growth processes. Poor adhesion with polymers, and seasonal biomass fluctuations can also affect the durability and consistency of acoustic materials production and performance. However, these challenges could potentially be mitigated by incorporating suitable binders. More research is needed to make better the use of aquatic plant and algae fibre acoustic materials, in particular to improve production process, assess long-term durability and develop the acoustical potential of sound absorption phenomena connected with reeds.

References

Akter, M., Uddin, M. H., & Anik, H. R. (2023). Plant fiber-reinforced polymer composites: A review on modification, fabrication, properties, and applications. *Polymer Bulletin*, *81*(1), 1–85. https://doi.org/10.1007/s00289-023-04733-5

Arnaud, L., & Gourlay, E. (2011). Experimental study of parameters influencing mechanical properties of hemp concretes. *Construction and Building Materials*, *28*(1), 50–56. https://doi.org/10.1016/j.conbuildmat.2011.07.052

Asdrubali, F., D'Alessandro, F., Schiavoni, S., & Mencarelli, N. (2015). Sound absorption properties of reed. In *Proceedings of the 22nd International Congress on Sound and Vibration* (pp. 1–8). Florence, Italy.

Astrauskas, T., Monin, V., & Januševičius, T. (2023). Sound absorption of dried brown, red, green algae. In A. Astolfi, F. Asdrubali, & L. Shtrepi (Eds.), *Proceedings of Forum Acusticum 2023*: *10th Convention of the European Acoustics Association*. European Acoustics Association. https://doi.org/10.61782/fa.2023.0013

Baley, C., Duigou, A. L., Morvan, C., & Bourmaud, A. (2018). Tensile properties of flax fibres. In *Handbook of properties of textile and technical fibres* (pp. 275–300). Woodhead Publishing. https://doi.org/10.1016/b978-0-08-101272-7.00008-0

Beheshti, M. H., Khavanin, A., Varyani, A. S., Yahya, M. N. B., Alami, A., Khajenasiri, F., & Talebitooti, R. (2021). Improving the sound absorption of natural waste material-based sound absorbers using micro-perforated plates. *Journal of Natural Fibres*, *19*(13), 5199–5210. https://doi.org/10.1080/15440478.2021.1875364

Beldam, M.-B. (2019). The importance of several room acoustic descriptors in operation rooms. In M. Ochmann, M. Vorländer, & J. Fels (Eds.), *Proceedings of the 23rd International Congress on Acoustics*: *Integrating 4th EAA Euroregio 2019* (pp. 4646–4653). Deutsche Gesellschaft für Akustik. https://doi.org/10.18154/RWTH-CONV-238817

Berry, P., Yassin, F., Grosshans, R., & Lindenschmidt, K. (2017). Surface water retention systems for cattail production as a biofuel. *Journal of Environmental Management*, *203*(Part 1), 500–509. https://doi.org/10.1016/j.jenvman.2017.08.019

Bonga, K. B., Bertolacci, L., Contardi, M., Paul, U. C., Zafar, M. S., Mancini, G., Marini, L., Ceseracciu, L., Fragouli, D., & Athanassiou, A. (2024). Mycelium agrowaste-bound biocomposites as thermal and acoustic insulation materials in building construction. *Macromolecular Materials and Engineering*, *309*(6), Article 2300449. https://doi.org/10.1002/mame.202300449

Cox, T., & D'Antonio, P. (2016). *Acoustic absorbers and diffusers*. Taylor & Francis / CRC Press. https://doi.org/10.1201/9781315369211

Das, S. C., La Rosa, A. D., Goutianos, S., & Grammatikos, S. A. (2022). Flax fibres, their composites and application. In *Plant fibers*, *their composites*, *and applications* (pp. 209–232). Elsevier. https://doi.org/10.1016/b978-0-12-824528-6.00017-5

Das, S. C., Srivastava, C., & Grammatikos, S. (2025). Accelerated aging of natural fiber composites (NFCs), their fabrication methods, industrial applications, challenges, and future directions: An overview. *Journal of Natural Fibres*, *22*(1), Article 2540480. https://doi.org/10.1080/15440478.2025.2540480

Deyholos, M. K., & Potter, S. (2013). Engineering bast fiber feedstocks for use in composite materials. *Biocatalysis and Agricultural Biotechnology*, *3*(1), 53–57. https://doi.org/10.1016/j.bcab.2013.09.001

Dong, W., Limin, P., Feng, F., Meihong, L., & Boqi, S. (2017). Analysis of polyester/wood composite fiber needling mat sound absorption performance. *Polymer Composites*, *39*(11), 3823–3830. https://doi.org/10.1002/pc.24480

Dubey, D., & Dutta, V. (2019). Nutrient enrichment in lake ecosystem and its effects on algae and macrophytes. In

V. Shukla & N. Kumar (Eds.), *Environmental concerns and sustainable development* (pp. 81–126). Springer. https://doi.org/10.1007/978-981-13-6358-0_5

Gumanová, V., Sobotová, L., Dzuro, T., Badida, M., & Moravec, M. (2022). Experimental survey of the sound absorption performance of natural fibres in comparison with conventional insulating materials. *Sustainability*, *14*(7), Article 4258. https://doi.org/10.3390/su14074258

Hashemi, Z., Monazzam Esmailpour, M., Nasirzadeh, N., Farvaresh, E., Beigzadeh, Z., & Salari, S. (2022). Estimation of sound absorption behavior of combined panels comprising kenaf fibres and micro-perforated plates below 2500 Hertz. *Journal of Health and Safety at Work*, *12*(4), 872–894.

International Organization for Standardization. (1996). *Acoustics — Determination of sound absorption coefficient and impedance in impedance tubes — Part 1*: *Method using standing wave ratio* (ISO Standard No. 10534-1:1996). https://www.iso.org/standard/18603.html

International Organization for Standardization. (1998). *Acoustics — Determination of sound absorption coefficient and impedance in impedance tubes — Part 2*: *Transfer function method* (ISO Standard No. 10534-2:1998). https://www.iso.org/standard/22851.html

Istana, B., Batan, I. M. L., Sutikno, Khem, S., Ubaidillah, U., & Yahya, I. (2023). Influence of particle size and bulk density on sound absorption performance of oil palm Frond-Reinforced composites particleboard. *Polymers*, *15*(3), Article 510. https://doi.org/10.3390/polym15030510

Jang, E.-S. (2023). Sound absorbing properties of selected green material—A review. *Forests*, *14*(7), Article 1366. https://doi.org/10.3390/f14071366

JavadSheikhMozafari, M. (2024). Enhancing sound absorption in micro-perforated panel and porous material composite in low frequencies: A numerical study using FEM. *Sound & Vibration*, *58*(1), 81–100. https://doi.org/10.32604/sv.2024.048897

Karaduman, Y. (2023). Bast fiber composites and their applications. In *Green sustainable process for chemical and environmental engineering and science* (pp. 167–193). Elsevier. https://doi.org/10.1016/b978-0-323-95167-8.00003-X

Kassim, D. H., Putra, A., & Ramlan, R. (2023). Enhancement of sound absorption of coir fiber using thin layer of kapok fibres. *Journal of Natural Fibres*, *20*(1), Article 2164103. https://doi.org/10.1080/15440478.2022.2164103

Khan, M. N., & Mohammad, F. (2014). Eutrophication: Challenges and solutions. In *Eutrophication*: *Causes*, *consequences and control* (pp. 1–15). Springer. https://doi.org/10.1007/978-94-007-7814-6_1

Klepeis, N. E., Nelson, W. C., Ott, W. R., Robinson, J. P., Tsang, A. M., Switzer, P., Behar, J. V., Hern, S. C., & Engelmann, W. H. (2001). The National Human Activity Pattern Survey (NHAPS): A resource for assessing exposure to environmental pollutants. *Journal of Exposure Science & Environmental Epidemiology*, *11*(3), 231–252. https://doi.org/10.1038/sj.jea.7500165

Kolya, H., & Kang, C. W. (2025). Sound absorption performance of wood: Influence of porosity, gas permeability, and back air cavities in five wood species. *European Journal of Wood and Wood Products*, *83*(6), Article 183. https://doi.org/10.1007/s00107-025-02335-8

Kristiansen, J., Persson, R., Lund, S. P., Shibuya, H., & Nielsen, P. M. (2011). Effects of classroom acoustics and self-reported noise exposure on teachers' well-being. *Environment and Behavior*, *45*(2), 283–300. https://doi.org/10.1177/0013916511429700

Lepak, W., Sterner, M., & Slaboch, P. (2018). Acoustic performance of additively manufactured reeds as an absorber. In *Proceedings of the INTER-NOISE/NOISE-CON Congress and Conference* (Vol. 258, No. 4, Article 00103). Institute of Noise Control Engineering. https://ince.publisher.ingentaconnect.com/content/ince/incecp/2018/00000258/00000004/art00103

Lim, Z., Putra, A., Nor, M., & Yaakob, M. (2017). Sound absorption performance of natural kenaf fibres. *Applied Acoustics*, *130*, 107–114. https://doi.org/10.1016/j.apacoust.2017.09.012

Liu, G., Chen, H., Yuan, Y., & Song, C. (2023). Indoor thermal environment and human health: A systematic review. *Renewable and Sustainable Energy Reviews*, *191*, Article 114164. https://doi.org/10.1016/j.rser.2023.114164

Liu, Y., Lyu, L., Xiong, X., Qian, Y., Li, H., & Guo, J. (2020). Structural characteristics and sound absorption properties of poplar seed fibres. *Textile Research Journal*, *90*(21–22), 2467–2477. https://doi.org/10.1177/0040517520921396

Lyu, L., Zhang, D., Tian, Y., & Zhou, X. (2021). Sound-Absorption performance and fractal dimension feature of Kapok Fibre/Polycaprolactone composites. *Coatings*, *11*(8), Article 1000. https://doi.org/10.3390/coatings11081000

Liu, R., Zhang, Z., & Zheng, X. (2025). The modern numerical and experimental methods for the sound absorbing characteristics of dissipative sound absorbing materials: A review. *Materials*, *18*(23), Article 5353. https://doi.org/10.3390/ma18235353

Liu, X., Tang, X., & Deng, Z. (2020). Sound absorption properties for multi-layer of composite materials using nonwoven fabrics with kapok. *Journal of Industrial Textiles*, *51*(10), 1601–1615. https://doi.org/10.1177/1528083720904926

Liu, Z., Zhan, J., Fard, M., & Davy, J. L. (2017). Acoustic measurement of a 3D printed micro-perforated panel combined with a porous material. *Measurement*, *104*, 233–236. https://doi.org/10.1016/j.measurement.2017.03.032

Malawade, U. A., & Jadhav, M. (2019). Investigation of the acoustic performance of Bagasse. *Journal of Materials Research and Technology*, *9*(1), 882–889. https://doi.org/10.1016/j.jmrt.2019.11.028

Miglioranza, K. S., De Moreno, J. E., & Moreno, V. J. (2004). Organochlorine pesticides sequestered in the aquatic macrophyte Schoenoplectus californicus (C.A. Meyer) Soják from a shallow lake in Argentina. *Water Research*, *38*(7), 1765–1772. https://doi.org/10.1016/j.watres.2004.01.017

Mohammadi, M., Taban, E., Tan, W. H., Din, N. B. C., Putra, A., & Berardi, U. (2024). Recent progress in natural fiber reinforced composite as sound absorber material. *Journal of Building Engineering*, *84*, Article 108514. https://doi.org/10.1016/j.jobe.2024.108514

Mohanty, A. K., Misra, M., & Drzal, L. T. (Eds.). (2005). *Natural fibres*, *biopolymers*, *and biocomposites*. Taylor & Francis / CRC Press. https://doi.org/10.1201/9780203508206

Mondal, S., Gautam, M., Das, R., Maddela, N. R., & Prasad, R. (2025). Sustainable antimicrobial and antioxidant packaging: Environmental implications and solutions. *Food Biosci-*

ence, *68*, Article 106347. https://doi.org/10.1016/j.fbio.2025.106347

Muhammad, M. M. bin, Sa'at, N. A., Nain, H., Isa, M. C., Nik Yussof, N. H., & Yati, M. S. D. (2012). The effect of air gap thickness on sound absorption coefficient of polyurethane foam. *Defence S and T Technical Bulletin*, *5*(2), 176–187.

Murray Gulde, C. L., Huddleston, G. M., Garber, K. V., & Rodgers, J. H., Jr. (2005). Contributions of Schoenoplectus californicus in a constructed wetland system receiving copper contaminated wastewater. *Water, Air, and Soil Pollution*, *163*(1–4), 355–378. https://doi.org/10.1007/s11270-005-1297-3

Mvubu, M. B., Anandjiwala, R., & Patnaik, A. (2019). Effects of air gap, fibre type and blend ratio on sound absorption performance of needle-punched non-woven fabrics. *Journal of Engineered Fibres and Fabrics*, *14*, 1–8. https://doi.org/10.1177/1558925019840874

Ndazi, B., Tesha, J. V., & Bisanda, E. T. N. (2006). Some opportunities and challenges of producing bio-composites from non-wood residues. *Journal of Materials Science*, *41*(21), 6984–6990. https://doi.org/10.1007/s10853-006-0216-3

Norton, M. P., & Karczub, D. G. (2003). *Fundamentals of noise and vibration analysis for engineers* (2nd ed.). Cambridge University Press. https://doi.org/10.1017/CBO9781139163927

Or, K. H., Putra, A., & Selamat, M. Z. (2016). Oil palm empty fruit bunch fibres as sustainable acoustic absorber. *Applied Acoustics*, *119*, 9–16. https://doi.org/10.1016/j.apacoust.2016.12.002

Pater, M. A., Świrk, P. R., Leniowska, L., & Reizer, R. (2025). The natural fibre composites and their acoustical performance. *Advances in Science and Technology Research Journal*, *20*(1), 259–268. https://doi.org/10.12913/22998624/211194

Putra, A., Or, K. H., Selamat, M. Z., Nor, M. J. M., Hassan, M. H., & Prasetiyo, I. (2018). Sound absorption of extracted pineapple-leaf fibres. *Applied Acoustics*, *136*, 9–15. https://doi.org/10.1016/j.apacoust.2018.01.029

Ramam, R. S., Pujari, S., Chigilipalli, B. K., Naik, B. D., Kottala, R. K., & Kantumuchu, V. C. (2024). Fabrication and optimization of acoustic properties of natural fiber reinforced composites. *International Journal on Interactive Design and Manufacturing* (*IJIDeM*), *18*, 3681–3689. https://doi.org/10.1007/s12008-023-01496-1

Rashid, M., Arshad, M., & Haq, E. U. (2025). Sustainable cellulose films as packaging (Coating) materials to reduce plastic use. In *Fuctionalized cellulose materials* (pp. 43–64). Springer. https://doi.org/10.1007/978-3-031-76953-5_2

Rodríguez, J. C., Alba, J., Arenas, J. P., & Del Rey, R. (2022). Estimating the airflow resistivity of porous materials in an impedance tube using an electroacoustic technique. *Applied Acoustics*, *201*, Article 109089. https://doi.org/10.1016/j.apacoust.2022.109089

Rusli, M., Irsyad, M., Dahlan, H., Gusriwandi, & Bur, M. (2019). Sound absorption characteristics of the natural fibrous material from coconut coir, oil palm fruit bunches, and pineapple leaf. *IOP Conference Series Materials Science and Engineering*, *602*(1), Article 012067. https://doi.org/10.1088/1757-899x/602/1/012067

Saad, M. J., & Kamal, I. (2012). Kenaf core particleboard and its sound absorbing properties. *Journal of Science and Technology*, *4*(2), 23–33.

Saleem, A., Medina, L., Skrifvars, M., & Berglin, L. (2020). Hybrid polymer composites of bio-based bast fibres with glass, carbon and basalt fibres for automotive applications—A review. *Molecules*, *25*(21), Article 4933. https://doi.org/10.3390/molecules25214933

Sambandamoorthy, S., Narayanan, V., Chinnapandi, L. B. M., & Aziz, A. (2020). Impact of fiber length and surface modification on the acoustic behaviour of jute fiber. *Applied Acoustics*, *173*, Article 107677. https://doi.org/10.1016/j.apacoust.2020.107677

Seddigh, A., Berntson, E., Jönsson, F., Danielson, C. B., & Westerlund, H. (2015). The effect of noise absorption variation in open-plan offices: A field study with a cross-over design. *Journal of Environmental Psychology*, *44*, 34–44. https://doi.org/10.1016/j.jenvp.2015.08.004

Sekar, V., Noum, S. Y. E., Putra, A., Sivanesan, S., Chin, K. C., Wong, Y. S., & Kassim, D. H. (2021). Acoustic properties of micro-perforated panels made from oil palm empty fruit bunch fiber reinforced polylactic acid. *Sound & Vibration*, *55*(4), 343–352. https://doi.org/10.32604/sv.2021.014916

Shuyun, S., Xiaozhi, G., Qichao, Z., & Kaining, C. (2016). Research on an emergency treatment technology for black-odor water caused by macrophytes decaying. *Journal of Lake Sciences*, *28*(3), 485–493. https://doi.org/10.18307/2016.0303

Strazdas, E., & Januševičius, T. (2024). Sound absorption evaluation and analysis of different hemp fiber types. In *CONECT. International Scientific Conference of Environmental and Climate Technologies* (p. 120). https://doi.org/10.7250/conect.2024.087

Su, W., Qian, X. M., Li, X. Y., & Liu, S. S. (2011). Influence of thickness and density of nonwoven sound-absorbing material on the sound-absorption capability. *Advanced Materials Research*, *197–198*, 440–443. https://doi.org/10.4028/www.scientific.net/amr.197-198.440

Summerscales, J., Dissanayake, N., Virk, A., & Hall, W. (2010). A review of bast fibres and their composites. Part 2 – Composites. *Composites Part A*: *Applied Science and Manufacturing*, *41*(10), 1336–1344. https://doi.org/10.1016/j.compositesa.2010.05.020

Tayong, R., Dupont, T., & Leclaire, P. (2011). Experimental investigation of holes interaction effect on the sound absorption coefficient of micro-perforated panels under high and medium sound levels. *Applied Acoustics*, *72*(10), 777–784. https://doi.org/10.1016/j.apacoust.2011.04.011

Tang, Y. C., & Cheng, H. D. (2025). Analysis and verification of optimization of micro-perforated panels' sound absorption using the Taguchi method. *The Journal of the Acoustical Society of America*, *157*(4), 3099–3111. https://doi.org/10.1121/10.0036504

Tang, X., & Yan, X. (2017). Acoustic energy absorption properties of fibrous materials: A review. *Composites Part a Applied Science and Manufacturing*, *101*, 360–380. https://doi.org/10.1016/j.compositesa.2017.07.002

Usta, C., Seyhan, A., & Gürarslan, A. (2024). Utilization of poplar fibres in needle punched nonwovens. *Cellulose*, *31*(13), 8351–8367. https://doi.org/10.1007/s10570-024-06062-w

Van Damme, B., Cavalieri, T., Nguyen, C., & Perrot, C. (2024). Enhancement of the sound absorption of closed-cell mineral foams by perforations: Manufacturing process and model-supported adaptation. *Materials & Design*, *249*, Article 113540. https://doi.org/10.1016/j.matdes.2024.113540

Wallius, V., & Näyhä, A. (2025). Wood-based textile innovations in the Finnish media: A critical discourse analysis. *Forest Policy and Economics*, *174*, Article 103492. https://doi.org/10.1016/j.forpol.2025.103492

Wang, G., Huang, R., & Fang, Y. (2023). Effects of temperature and algae biomass on algae decay and the production of dimethyl trisulfide. *Applied Ecology and Environmental Research*, *21*(6), 5595–5605. https://doi.org/10.15666/aeer/2106_55955605

Wille, V. K. D., Pedrazzi, C., Colodette, J. L., De Oliveira, R. C., Coldebella, R., Giesbrecht, B. M., & De Oliveira Saccol, A. F. (2017). Cellulose pulp produced from bulrush fiber. *Ciência Rural*, *47*(5). https://doi.org/10.1590/0103-8478cr20160652

Xiang, H., Wang, D., Liua, H., Zhao, N., & Xu, J. (2013). Investigation on sound absorption properties of kapok fibres. *Chinese Journal of Polymer Science*, *31*(3), 521–529. https://doi.org/10.1007/s10118-013-1241-8

Xue, Y., Du, Y., Elder, S., Devin, S., Horstemeyer, M., & Zhang, J. (2007, May). Statistical tensile properties of kenaf fibres and its composites. In *9th International Conference on Wood & Biofiber Plastic Composite* (Vol. 22). Forest Products Society.

Yahya, K., Haron, Z., Hamid, S. N. S. A., Fasli, N. M., & Taiwo, E. M. (2019). The potential of pineapple leaf fibre as an acoustic absorber. In F. Mohamed Nazri (Ed.), *Lecture notes in civil engineering*: *Vol. 53. Proceedings AICCE'19* (pp. 919–931). Springer. https://doi.org/10.1007/978-3-030-32816-0_68

Yang, T., Hu, L., Xiong, X., Petrů, M., Noman, M. T., Mishra, R., & Militký, J. (2020). Sound absorption properties of natural fibres: A review. *Sustainability*, *12*(20), Article 8477. https://doi.org/10.3390/su12208477

Yildiz, A. Y., & Öztekin, S. (2024). Utilization of fruit and vegetable wastes in food packaging. In A. K. Mohanty, M. Misra, & L. T. Drzal (Eds.), *Natural fibres*, *biopolymers*, *and biocomposites* (pp. 197–218). Taylor & Francis/CRC Press. https://doi.org/10.1201/9781003453277-9

Yoshioka, R. M., Galloway, A. W. E., Schram, J. B., Bell, L. E., & Kroeker, K. J. (2025). Benthic marine invertebrate herbivores diversify their algal diets in winter. *Ecosphere*, *16*(1), Article e70135. https://doi.org/10.1002/ecs2.70135

Yu, Y., Wang, Q., & Wang, P. (2019). Bioprocessing of bast fibres. In A. Cavaco-Paulo, V. A. Nierstrasz, & Q. Wang (Eds.), *Advances in textile biotechnology* (pp. 1–19). Woodhead Publishing. https://doi.org/10.1016/b978-0-08-102632-8.00001-3

Zhang, C., Li, J., Hu, Z., Zhu, F., & Huang, Y. (2012). Correlation between the acoustic and porous cell morphology of polyurethane foam: Effect of interconnected porosity. *Materials* & *Design*, *41*, 319–325. https://doi.org/10.1016/j.matdes.2012.04.031

Zulkifli, R., Zulkarnain, & Nor, M. J. M. (2010). Noise control using coconut coir fiber sound absorber with porous layer backing and perforated panel. *American Journal of Applied Sciences*, *7*(2), 260–264. https://doi.org/10.3844/ajassp.2010.260.264