SUSTAINABILITY ASSESSMENT OF MATERIALS AND METHODS FOR ENHANCING ACOUSTIC INSULATION SYSTEMS

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The growing demand for environmentally sustainable construction materials has led to increased research into alternative solutions for noise control. This paper presents a survey of sustainable acoustic materials, with a particular focus on recycled textile hemp-based insulation systems. While natural and recycled materials offer significant ecological advantages, their acoustic performance often lags behind conventional synthetic solutions. The study highlights recent advancements in plasma surface treatment of polymeric materials as an innovative and environmentally friendly method for enhancing the acoustic properties of recycled textiles. By modifying fibre surface morphology and improving airflow resistivity, plasma treatment significantly enhances sound absorption and insulation capabilities. The integration of recycled hemp based materials with plasma technology represents a promising pathway toward high-performance, low-impact acoustic solutions aligned with circular economy principles.

Key words: *noise control, sound absorption coefficients (SAC), sustainable acoustic materials, plasma treatment, Life Cycle Assessment (LCA).*

1. Introduction

Noise pollution is recognized as a major environmental issue affecting human health and well-being. The construction sector plays a critical role in mitigating noise through the use of effective sound insulation and absorption materials. Traditional acoustic materials, such as mineral wool, glass fibre, and polymer-based foams, provide good acoustic performance but are associated with significant environmental drawbacks, including high embodied energy, non-renewable resource consumption, and challenges in end-of-life disposal [1,2]. In response, research has increasingly focused on sustainable acoustic materials, particularly those derived from natural and recycled sources [3-8]. Among these, recycled textile materials have emerged as a promising solution due to their fibreous structure and availability as post-consumer waste [9,10]. Potential raw materials include recycled cotton, polyester, wool, denim, cellulose-based fibres, and textile waste blends, which can be processed into nonwoven mats, fibrous panels, and other porous structures suitable for sound absorption applications. The global textile sector faces significant sustainability challenges due to its high water and chemical consumption and associated wastewater production. Traditional textile finishing methods, such as bleaching,

scouring, and dyeing, rely heavily on aqueous chemistries that contribute to environmental pollution and resource depletion. Plasma treatment is emerging as a promising alternative for surface functionalization of fibers without affecting the bulk properties of textiles. It involves the interaction of energetic species — ions, radicals, and photons — with fiber surfaces to induce chemical and physical modifications. Plasma-based processes are inherently dry, rapid, and capable of treating a wide range of materials, including natural and synthetic fibers. Depending on the plasma type, gas composition, power, pressure, and treatment time, plasma can modify surface morphology, roughness, chemical composition, surface energy, and wettability while the modification remains primarily confined to the fibre surface [11,12]. In the case of fibrous acoustic materials, such modifications may influence the structure and interaction of the fibre network and, consequently, the propagation and dissipation of sound within the porous material.

An additional approach for modifying the functional properties of fibrous materials is surface treatment using low-temperature plasma. The application of low-temperature plasma treatment to improve the acoustic performance of fibrous materials has already been investigated. Pavlović et al. [13] examined the acoustic properties of natural cellulose materials, including cotton and hemp, treated using radio-frequency argon plasma and reported an increase in the sound absorption coefficient for selected plasma-treatment conditions. The authors related the acoustic changes to plasma-induced structural and chemical modifications of the fibre surface. Similarly, Na and Cho [14] investigated plasma treatment of polyester, jute, and kenaf nonwoven fabrics intended for automotive acoustic applications. Their results demonstrated that plasma treatment can modify sound absorption, pore size, fabric weight, and viscoelastic properties, although the effect depends strongly on the type of fibre. More recently, reviews of textile-based sound-absorbing materials have identified plasma treatment among the physical and chemical approaches capable of modifying fibre morphology and surface characteristics to influence sound absorption [15]. This work builds on previous research concerning plasma modification of textile fibres and its influence on acoustic properties [13], while focusing attention on the opportunities and sustainability contribution associated with applying this approach to recycled textile materials, which is less investigated. The present paper provides a survey of sustainable acoustic materials, with particular emphasis on recycled textile-based materials, and discusses plasma surface treatment as a promising approach for improving the performance of recycled textile insulation systems.

2. Sustainability contribution assessment

Sustainability is commonly defined as the capacity to maintain resource availability for future generations while minimizing environmental and societal impacts. In this sense, a material or product can be regarded as sustainable if its production and use do not lead to resource depletion, excessive waste generation, or environmental pollution, and if they ensure safe and equitable conditions for workers and communities.

In the field of acoustic insulation, a growing body of research [15-25] has focused on developing alternative materials to replace conventional solutions such as glass wool and rock wool, which have a high negative environmental impact because of a high carbon footprint during production and also due to their landfill disposal burdens due to limited recycling stream. These alternatives include both natural materials, such as cotton, cellulose, hemp, wool, and clay, and recycled resources, including rubber, plastics, carpets, and cork. Such materials are particularly attractive due to their lower environmental footprint and potential for circular use.

The environmental performance of materials and products is commonly assessed using standardized methodologies, including Life Cycle Assessment (LCA), supported by databases such as Ecoinvent and Ecoprofiles [25,26]. When applied to buildings, LCA studies typically indicate that energy savings achieved during the operational phase significantly outweigh the environmental impacts associated with the production of insulation materials [27].

Nevertheless, further reductions in environmental impact remain necessary. In response, insulation materials derived from renewable resources have gained increasing attention and market presence. In addition to providing adequate thermal performance and heat storage capacity, these bio-based materials contribute to carbon sequestration during their service life and offer potential end-of-life advantages, such as biodegradability or substitution of fossil-based materials. Consequently, they represent a promising pathway toward more sustainable building systems.

2.1. Materials

The true sustainability of a product must be assessed across its entire life cycle, from cradle to grave. For this purpose, Life Cycle Assessment (LCA) can be used to evaluate the potential environmental impacts associated with every stage of a product's life cycle. Material extraction, production, transport, construction, operation and management, de-construction and disposal, recycling and reuse have therefore to be taken into account. Ecoinvent [26] is a Swiss LCA database which takes into account the following impact assessment results: Cumulated Energy Demand (CED) and Non-Renewable Energy (NRE) fraction, Global Warming Potential (GWP) and Acidification Power (AP) [26].

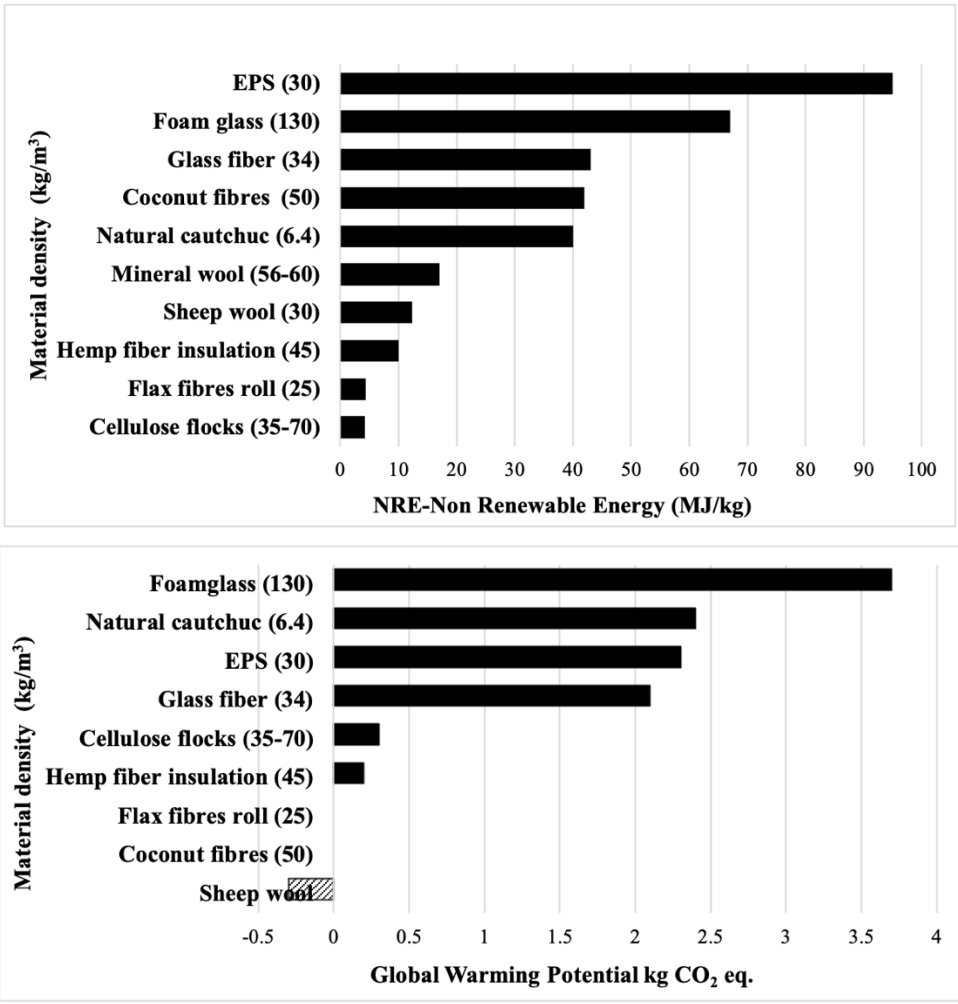

Figure 1: Ecoinvent. Comparison of environmental impacts of traditional and natural materials. Some of data used for comparisons are from Refs. [26,27].

A comparison based on the Ecoinvent database between the environmental impacts of some traditional and natural sound insulation materials from cradle to grave is shown in Fig. 1: cellulose, flax and sheep wool have the lowest impacts on the considered categories. An estimation of the use of primary energy for the extraction, transport, production and packing of different insulating materials is reported in Fig. 2. As it can be seen, a "green" material (e.g., flax) does not always require less energy over its life cycle than a traditional one (e.g., rock wool), while synthetic plastic fibres consistently show the greatest impacts, especially in terms of fossil fuel consumption.

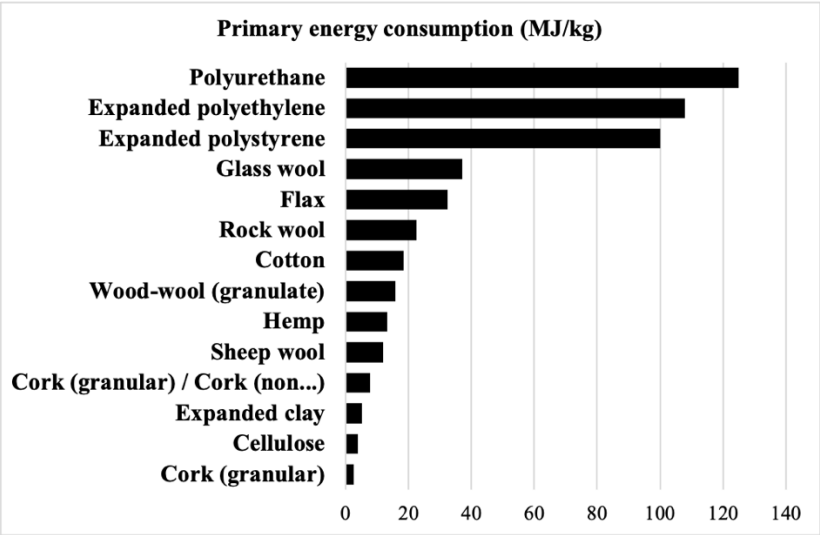

Figure 2: Estimation of primary energy consumption of some sound insulating materials' life cycles. Some of data used for comparisons are from Refs. [26,28]

Also, it can be seen that hemp-based materials have very low primary energy consumption, which is also one of the reasons that hemp, among other natural materials such as kenaf, flax, sisal, cork, sheep wool, bamboo, or coconut fibres, often show good absorption performance and can therefore be used as sound absorbers in room acoustics and noise barriers [29,30]. The acoustic and thermal properties and costs of some traditional and sustainable natural insulating materials are reported in Tab. 1. When not specified, the absorption coefficient and cost refer to 4 cm thick panels, while the index of impact noise reduction refers to 2 cm thick panels.

Table 1. Acoustic and thermal properties and costs of some traditional and natural insulating materials. Some of data used for comparisons are from Refs. [27], [28], [33]

	Thermal conductivity λ (W/mK)	Absorption coefficient α at 500 Hz (-)	Index of reduct. of impact noise ΔLW (dB)	Cost (€/m^2)
Hemp	0.040	0.60 (30 cm)		5
Kenaf	0.040	0.74 (5 cm)		
Coco fibre	0.043	0.42	23	
Sheep wool	0.044	0.38 (6 cm)	18	
Wood wool	0.065	0.32	21	12
Cork	0.039	0.39	17	19
Cellulose	0.037	1.00 (6 cm)	22	
Flax	0.040	-		7
Glass wool	0.040	1.00 (5 cm)		12
Rock wool	0.045	0.90 (5 cm)		6

Expanded polystyrene	0.031	0.50	30	10

2.1.1 Natural Sound absorption materials

Many natural materials as kenaf, flax, sisal, hemp, cork, sheep wool, bamboo or coconut fibres [17-23,31,32] show good absorbing performances and can therefore be used as sound absorbers in room acoustics and noise barriers (Tab. 1 and Fig. 3). The frequency dependence of sound absorption is particularly important in building acoustics because different noise sources and acoustic phenomena dominate different frequency regions. The low-frequency range (approximately 100–250 Hz) is associated with traffic, mechanical equipment and other low-frequency noise sources and is generally more difficult to control using conventional porous absorbers. The mid-frequency range (approximately 250–2000 Hz) is highly relevant to speech, indoor communication and room-acoustic conditions, whereas the higher-frequency range (approximately 2000–5000 Hz) contributes significantly to the control of reverberation and high-frequency components of indoor noise. This frequency range is also consistent with standardized acoustic characterization: ISO 354 specifies sound absorption measurements in one-third-octave bands from 100 to 5000 Hz, while ISO 11654 uses frequency-dependent absorption data for rating sound absorbers intended for building applications. Consequently, the 100–5000 Hz range is considered the primary range of interest for evaluating the acoustic performance of the materials discussed in this study. At 500 Hz, nevertheless, the absorption coefficient of synthetic materials is generally superior to the one of natural materials. Expanded clay, which may also be considered a natural product, shows good sound absorption performance over a wide frequency range (higher than 0,80 in the range 500-5000 Hz) [31]. Several natural materials are commonly used as thermal and acoustical insulation in multilayered walls: among these flax, coconut, cotton, sheep wool and kenaf mats are the most present on the market [23, 24, 31]. Their sound and thermal insulation performances are in many cases as good as those of traditional materials (Tab. 1 and Fig. 3): many studies have demonstrated that the sound insulation of double-leaf walls with low density animal wool (sheep wool) or heavy vegetal wool (latex-coco) is equal or better than the one of walls with mineral wool or polystyrene of the same thickness [19, 27]. As for natural materials, the less they are treated, the better they perform in terms of energy saving; native materials should be preferred to reduce transport energy. Moreover, natural fibres have negative impacts as far as climate change (CO_2 absorption). Nevertheless, other performances have to be considered: vegetal fibres are more subject to fungal and parasites attack and are less resistant to fire than mineral fibres. The non-toxicity of the chemical products used for cultivation must be taken into account too.

2.1.2 Recycled materials

Many recycled materials, such as waste rubber, metal shavings, plastic, textile agglomerates can be used to prepare acoustic materials. It can be useful to mix various recycled materials of different granulometries to obtain the desired performances; in these cases, a binder or glue have to be added in a proper proportion.

The most commonly used recycled material for improving the sound environment in enclosed spaces is cellulose obtained from used newspapers, to which flame retardants and biocides are added.

Wet cellulose fibres are generally sprayed directly on walls or ceilings and their sound absorption properties are even better than those of mineral wool. Other promising materials are metal shavings and textile agglomerates, recycled textiles and waste [13-16]. Rubber crumbs are good acoustic materials with a broadband absorption spectrum and are particularly suitable for traffic noise barriers, also due to their durability [32].

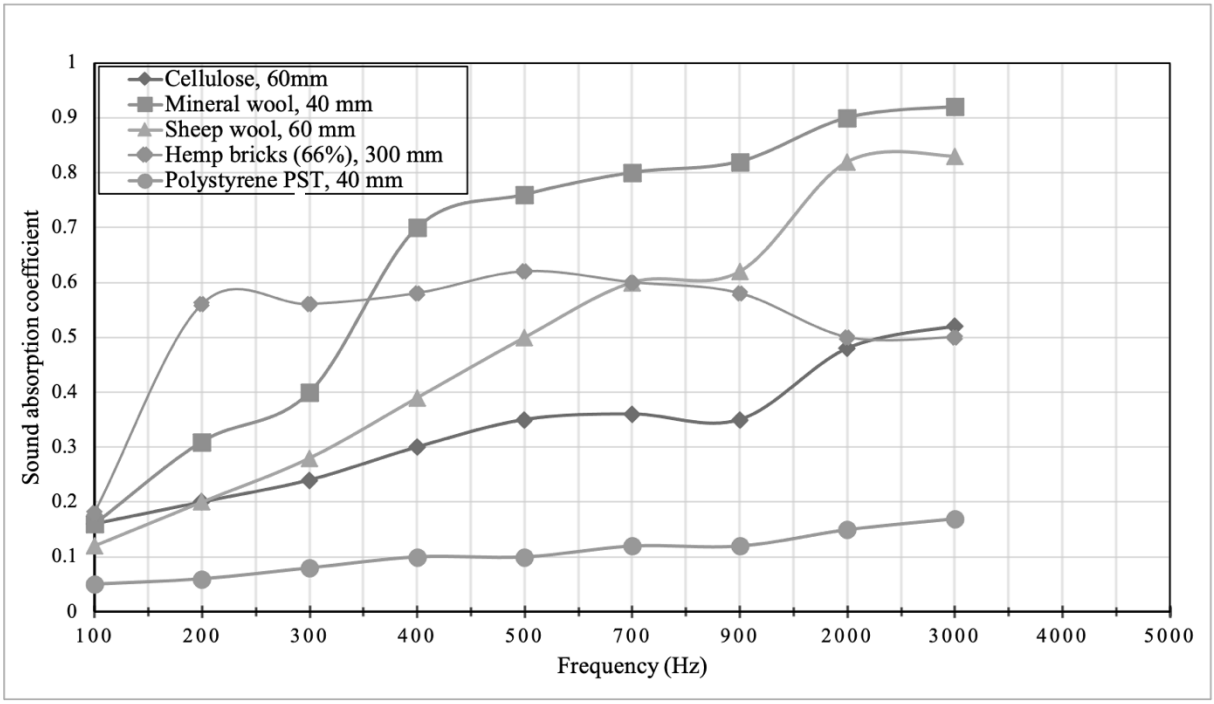

Figure 3: Sound absorption coefficient of natural and traditional materials. Some of data used for comparisons are from Ref. [5]

2.1.3 Hemp based materials

Hemp based materials show good absorbing performances and can therefore be used as sound absorbers in room acoustics and noise barriers (Tab.1, Fig.3 and Fig. 4).

Among all plant fibres, hemp is one of the most interesting because of its excellent properties, low cost, and high cellulose content. The research revealed that: the sequence of sound-absorbing performance of several fibre aggregates was cotton fibre, waste hemp fibre, wool fibre, and polyester fibre; that waste hemp fibre had excellent high-frequency sound-absorbing performance, with a maximum sound absorption coefficient of 0.95; and that the maximum sound absorption coefficient of the waste hemp fibre composite reached 0.93 (Fig. 4) [34]. Therefore, the waste hemp fibre has excellent sound-absorbing properties and has high application value in the field of sound absorption.

The structure of hemp fibre is quite different from most other fibres. There are various shapes of cavities in the cross-section, spiral patterns, connected holes, and cracks in the longitudinal surface, which make domestic and foreign scholars interested in the application hemp fibre in the field of acoustics-related research [34,35]. The ability of sound-absorbing materials is mainly determined by the average sound absorption coefficient, α (SAC) and noise reduction coefficient (NRC). For materials, when the average

sound absorption coefficient (SAC) is greater than 0.2, they can be classified as sound-absorbing materials. When the average sound absorption coefficient is greater than 0.56, they are known as high-efficiency sound-absorbing materials [36].

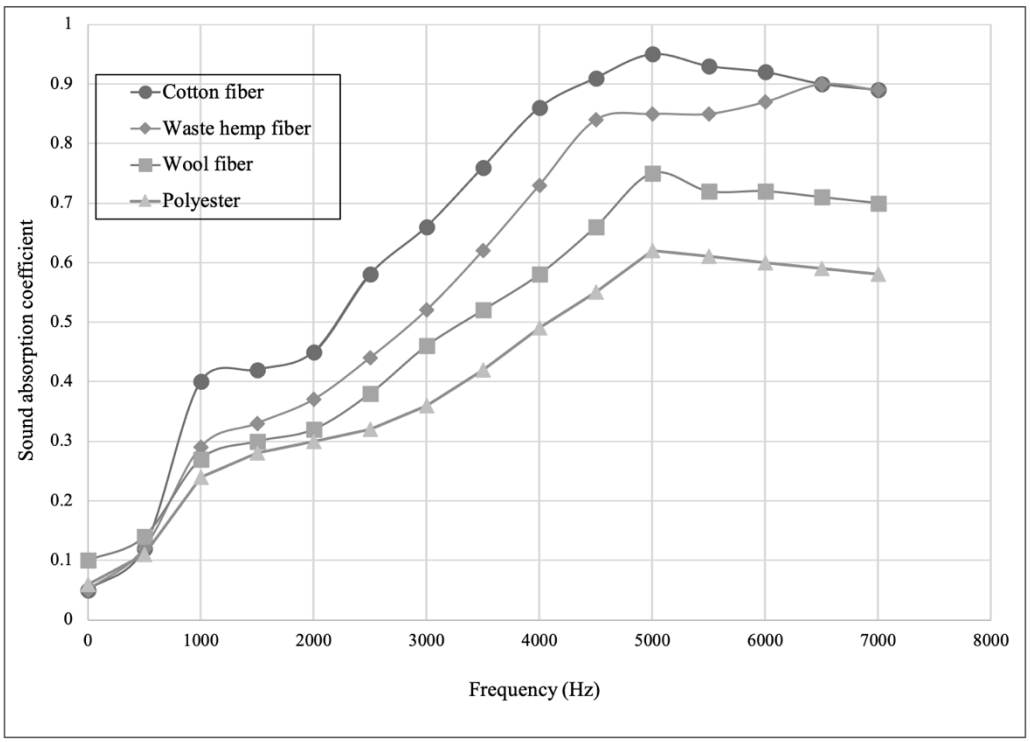

Figure 4: The sound-absorbing coefficient curve of the fiber aggregate. Some of data used for comparisons are from Ref. [34]

Hemp farming requires relatively less water [37,38] due to being grown in regions with moderate temperatures and adequate rainfall [39,40]. Hemp is a hardy plant that requires relatively little fertilizer and pesticide use [37,41] and absorbs large amounts of CO_2 from the ambient air, making it a sustainable choice among natural fibres[42]. Zimniewska (2022) reported that 1 hectare (ha) of hemp crop can absorb 10 tons (t) of CO_2 from the air annually. To compare these fibres and address environmental issues in the textile and apparel industry, researchers employ LCA [45,46] to quantify the environmental impacts of products and processes by accounting for all inputs and associated emissions to water, soil, and air. The majority of hemp LCA studies have focused on the agricultural phase of hemp, hemp as construction material, hemp paper, hemp composites, and hemp as a biofuel (S6). However, LCA studies on hemp as a fibre for textile and apparel applications remain limited due to a lack of data on hemp textile production in LCA databases [39]. Hemp could be a sustainable alternative to cotton due to its lower input requirements, including water and fertilizers. However, its tactile and mechanical properties differ significantly from those of cotton [47].

Table 2 shows the values of different environmental parameters in the production of 1 kg of hemp fibres and 1 kg of glass fibres [44]. The lower energy consumption and reduced greenhouse gas emissions give natural fibres a clear advantage compared to glass fibre.

Table 2. Environmental parameters in production of 1 kg of fibres Some of data used for comparisons are from Refs. [44]

Parameters	Hemp fibre	Glass fibre
Power consumption (MJ)	3.40	48.30
CO2 emission (kg)	0.64	20.40
SOx emission (g)	1.20	8.80
NOx emission (g)	0.95	2.90
BOD (mg)	0.27	1.80

2.2. Plasma treatment

Experimental and literature-based analysis demonstrate that plasma treatment significantly increases surface roughness, introduces microporosity, and alters chemical bonding, leading to improved thermal resistance and sound absorption characteristics [48].

The plasma process, owing to its dry, low-energy nature, dramatically reduces the water and chemical footprint compared with traditional wet finishing. Two different methods of hydrophobic textile finishing, a traditional liquid-based pad-dry curing and a novel gas-based plasma treatment, have been studied to estimate their environmental impact and the total treatment cost. The study presents the environmental impact of the conventional cotton pad-dry-cure process in comparison with the base scenario (5-min treatment, with a C_2F_6 flow rate equal to 13 cm^3/min) for the low-pressure-low-temperature plasma treatment method. The plasma treatment process is significantly more environmentally friendly than the cotton pad-dry-cure process. The environmental impact of the plasma treatment method is lower both for the single score indicator and for each environmental impact indicator separately [49].

2.2.1 Knitted fabric acoustic properties plasma modification

For the modification of the cotton/hemp knitted fabrics, we used the plasma treatment in the RF capacitively coupled plasma (CCP) reactor filled by the N_2 – Ar gas mixture. The measurements of the sound absorption coefficient (SAC) of the examined materials were performed before and after plasma treatments. The SAC spectra for both untreated and the plasma treated sample, in the frequency range from 0 Hz to 5200 Hz, are presented in Fig. 5 [50]. We used a standard two-microphone impedance tube which has been designed as per the ISO 10534-2:1998 standard (Acoustics-Determination of sound absorption coefficient and impedance in impedance tubes-Part 2: Transfer-function method). The diameter of the tube (29 mm) was set up for measuring SAC in the high frequency range (up to 5200 Hz).

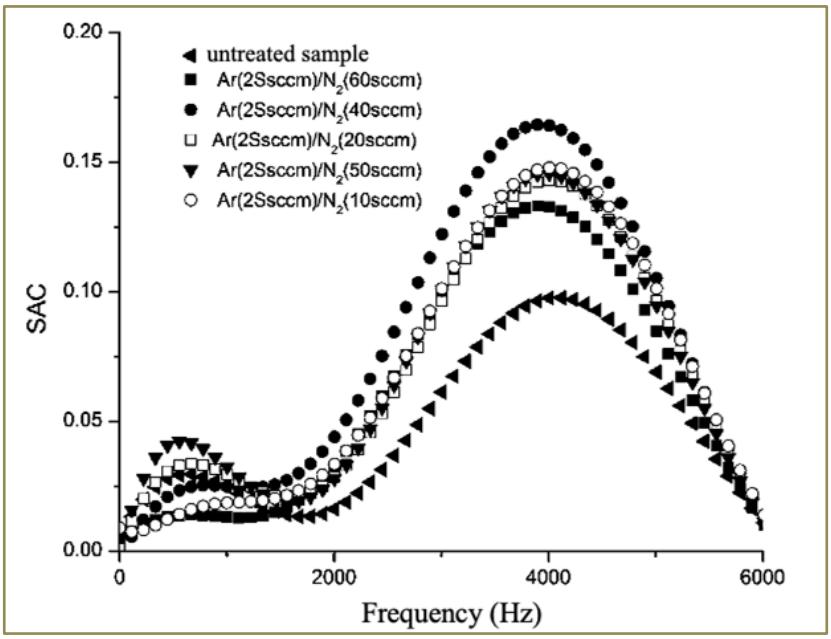

Figure 5. Sound absorption coefficients of the representative sample of treated material [50]

As shown in Fig. 5, the sound absorption coefficient (SAC) increased across almost the entire frequency range, with the most pronounced improvement observed at medium and high frequencies between 3000 and 4500 Hz. As can be seen from the figures, the knitted fabrics are characterized by higher SAC in the whole frequency range after the plasma treatment. Figure 5 shows that the maximum increase in the sound absorption coefficient (SAC) after treatment with N_2–Ar plasma was approximately 60% at 4000 Hz.

The modification of the acoustical properties of the natural cellulose materials was related to their structural micro-mechanical changes, such as a decrease in the fibres' stiffness and an increase in their diameter. For porous absorbers, the absorption coefficient α at a given frequency f is related to the thickness d and the material properties (flow resistivity, density, etc.) through the Delany–Bazley model or empirical formulas (Eq. (1)):

$$\alpha(f) \approx \frac{0.16\left(\frac{\rho c}{\sigma}\right)fd}{1+0.16\left(\frac{\rho c}{\sigma}\right)fd} \quad (1)$$

Where:

ρ = air density (~1.2 kg/m³)

c = speed of sound in air (~343 m/s)

σ=flowresistivity of material (Pa·s/m²)

f = frequency (Hz)

d = thickness (m)

This shows that absorption increases with thickness and with higher frequencies.

A common simple model (Eq. (2)) that can be obtained from Eq. (1) (from empirical acoustics) is:

$$\alpha \approx \frac{kd}{1+kd} \quad (2)$$

Where:

α = absorption coefficient

d = thickness of material

k = frequency-dependent constant (depends on flow resistivity, frequency, etc.)

Inverting the relationship and combining Eqs. (1) and (2) yields the expression for thickness given in Eq. (3):

$$d_1 = \frac{\alpha_1}{k(1-\alpha_1)} \tag{3}$$

Let α_1 and d_1 represent the absorption coefficient and thickness of the original sample, respectively, while α_2 and d_2 represent those of the treated sample.:

For α increases by 60% as can be noticed in Eq. (4):

$$\alpha_2 = \alpha_1 \times 1.60 \tag{4}$$

Then the new thickness should be calculated with Eq. 5:

$$d_2 = \frac{\alpha_2}{k(1-\alpha_2)} = \frac{1.6\,\alpha_1}{k(1-1.6\alpha_1)} \tag{5}$$

From Eq.(3) and Eq. (4), relative thickness change is presented with Eq. (6):

$$\frac{d_2}{d_1} = \frac{1.6\,\alpha_1/(1-1.6\alpha_1)}{\alpha_1/(1-\alpha_1)} = \frac{1.6\,(1-\alpha_1)}{1-1.6\,\alpha_1}. \tag{6}$$

Eq. (7) shows how thickness must change to achieve a 60% higher absorption coefficient.

Say original α_1=0.1:

$$\frac{d_2}{d_1} = \frac{1.6\cdot(1-0{,}1)}{(1-1.6\cdot 0.1)} \approx 1.7 \tag{7}$$

Thickness needs to be 1.7 times higher without plasma modification (Eq. 7). For the investigated hemp knitted fabric structure (areal density ≈ 0.98 kg/m²), a 60% increase in the sound absorption coefficient achieved by plasma treatment allows a reduction of approximately 40% in material usage per unit area. For an initial absorption coefficient of 0.1, a 60% improvement achieved through plasma treatment corresponds to a material saving of approximately 0.39–0.41 kg/m², while maintaining equivalent acoustic performance. The increases of absorption coefficient as the thickness increases is confirmed by other authors. Numerous studies that dealt with sound absorption in porous materials have concluded that low frequency sound absorption has direct relationship with thickness. A commonly used rule of thumb suggests that effective sound absorption in porous absorbers occurs when the material thickness is on the order of one-tenth of the wavelength of the incident sound [10]. Peak absorption occurs at a resonant frequency of one-quarter wavelength of the incident sound (ignoring compliance effect) [16]. A study by Ibrahim et al., showed the increase of sound absorption only at low frequencies, as the material gets thicker. However, at higher frequencies, thickness has an insignificant effect on sound absorption [17].

2.2.2 Environment impact assessment

Plasma surface modification significantly enhances the sound absorption performance of hemp-based knitted fabrics by increasing surface roughness and airflow resistivity, leading to improved acoustic energy dissipation. A 60% increase in the absorption coefficient enables a reduction of approximately 40% in material usage while maintaining equivalent acoustic performance. Together with the inherent sustainability of hemp fibers, these results suggest that this approach provides an efficient and environmentally favorable solution for acoustic insulation applications. Obtained plasma treatment of material surface environment impact is presented in Fig. 6.

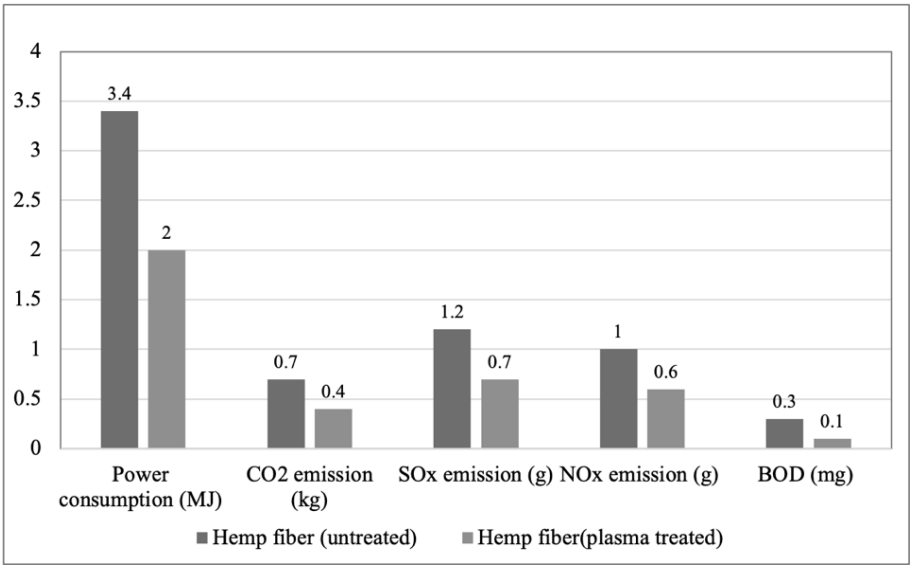

Figure 6. Plasma material surface treatment environment impact

3. Conclusions

Plasma surface modification significantly enhances the sound absorption performance of hemp-based knitted fabrics by increasing surface roughness and airflow resistivity, leading to improved acoustic energy dissipation. A 60% increase in the absorption coefficient enables a reduction of approximately 40% in material usage while maintaining equivalent acoustic performance. These results, combined with the inherent sustainability of hemp fibers, make this approach an effective and environmentally friendly solution for the application of acoustic insulation. This breef sustainability assessment analysis demonstrates that plasma-treated hemp fabrics exhibit a significant step forward in improving the relationship between new insulation materials technologies and environmental impact. Unlike conventional materials, where improved sound absorption requires increased material thickness and associated environmental burdens, plasma modification enables higher absorption coefficients with reduced material mass. This results in a decrease of approximately 40% in material usage and up to 60% in CO_2 emissions per kg. Additionally, the elimination of water and chemical processing further enhances sustainability. The combined effect represents a decoupling of performance and environmental impact, positioning

plasma-treated hemp textiles as an efficient and sustainable acoustic solution. In this way, plasma-induced insulator surface modifications represent a powerful technology for improving quality of life by enhancing noise protection in the living environment. At the same time, this technology is environmentally friendly, due to its efficiency in reducing water consumption and CO2 emissions during the production process.

Acknowledgment

This work was supported in part by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia under contract No. 451-03-34/2026-03/200162.

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Submitted: 06.05.2026.
Revised: 15.08.2026.
Accepted: 21.08.2026.