



SUSTAINABILITY ASSESSMENT OF AN APPLIED METHOD FOR ENHANCING THE ACOUSTIC PROPERTIES OF HEMP-BASED TEXTILE INSULATION SYSTEMS

Scientific paper
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Sanja Pavlović¹

¹Academy of Applied Studies Polytechnic, Belgrade, Serbia,
E-mail: spavlovic@politehnika.edu.rs, ORCID ID: 0000-0002-9596-8393

ABSTRACT: The demand for sustainable and high-performance acoustic materials has led to increased interest in textile-based sound insulation systems. However, natural and recycled textile materials often exhibit lower acoustic efficiency compared to conventional synthetic insulations. This paper investigates the potential of plasma surface treatment as an environmentally friendly method to enhance the acoustic performance of textile-based insulation materials, with a particular focus on recycled textile hemp-based insulation systems. Plasma treatment modifies fiber surface morphology and chemistry, improving airflow resistivity and internal friction—key parameters influencing sound absorption and insulation. The study also evaluates the ecological implications of plasma treatment, demonstrating its advantages over traditional chemical processing methods. The results indicate that plasma-treated textiles can achieve improved acoustic performance while reducing environmental impact, making them a promising solution for sustainable building acoustics.

Keywords: Sustainable acoustic materials, Life Cycle Assessment (LCA), hemp- based materials, plasma treatment, sound absorption coefficients (SAC), Environment impact.

PROCENA ODRŽIVOSTI PRIMENJENE METODE ZA POBOLJŠANJE AKUSTIČNIH SVOJSTVA TEKSTILNIH IZOLACIONIH SISTEMA NA BAZI KONOPLJE

APSTRAKT: Potražnja za održivim i visoko efikasnim akustičnim materijalima dovela je do povećanog interesovanja za sisteme zvučne izolacije na bazi tekstila. Međutim, prirodni i reciklirani tekstilni materijali često pokazuju nižu akustičnu efikasnost u poređenju sa konvencionalnim sintetičkim izolacijama. Ovaj rad istražuje potencijal površinske obrade materijala plazmom kao ekološki prihvatljive metode za poboljšanje akustičnih performansi izolacionih materijala na bazi tekstila, sa posebnim fokusom na izolacione sisteme na bazi recikliranog tekstila od mešavine konoplje. Obrada plazmom modifikuje morfologiju i hemijski sastav površine vlakana, poboljšavajući otpornost protoka vazduha



i unutrašnje trenje - ključne parametre koji utiču na apsorpciju zvuka i zvučnu izolaciju. Studija takođe procenjuje ekološke implikacije obrade plazmom, demonstrirajući njene prednosti u odnosu na tradicionalne metode hemijske obrade. Rezultati ukazuju da tekstil tretiran plazmom može postići poboljšane akustične performanse uz smanjenje uticaja na životnu sredinu, što ga čini perspektivnim rešenjem za održivu akustičku izolaciju u građevini.

Ključne reči: Održivi akustični materijali, procena životnog ciklusa (LCA), materijali na bazi konoplje, tretman plazmom, koeficijenti apsorpcije zvuka (SAC), uticaj na životnu sredinu.

1. INTRODUCTION

Increasing consumer awareness and environmental concerns have significantly influenced the development of sustainable materials in the textile industry. The entire textile life cycle—from raw material extraction to disposal—contributes to environmental degradation through high energy consumption, water usage, and chemical emissions [1], [2]. Natural fibers such as cotton, wool, and flax possess considerable ecological footprints related to cultivation and processing, while synthetic fibers present environmental challenges due to their fossil-based origins and long degradation times [1], [3]. Therefore, recycling and reuse of textile materials have become essential strategies within the framework of a circular economy [4]. In recent years, hemp fibers have gained attention as a sustainable alternative due to their low environmental impact, biodegradability, and favorable mechanical properties [5], [6]. Furthermore, the use of recycled hemp-based textiles, especially in knitted structures, contributes to sustainable material development due to their renewability, porosity, and suitability for acoustic applications [6], [7]. Plasma treatment has additionally emerged as an environmentally friendly surface modification technology because it reduces water and chemical consumption and eliminates wastewater generation associated with conventional wet processing methods [8], [9].

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Beyond sustainability, modern textiles are increasingly required to provide functional performance, including thermal insulation and acoustic absorption. These properties are particularly relevant for applications in building materials, automotive interiors, and technical textiles.

Surface modification techniques, such as plasma treatment, have shown significant potential in enhancing fiber surface characteristics, including: increased surface roughness, improved porosity, modified airflow resistivity [18].

The aim of this study is to investigate the combined effect of plasma treatment and the incorporation of hemp-based materials on the acoustic and sustainability performance of



recycled cellulose knitted textiles. By integrating eco-friendly materials with advanced surface engineering, this research seeks to contribute to the development of next-generation sustainable acoustic insulation systems.

2. MATERIALS AND METHODS

The sustainability assessment of plasma-modified hemp knitted fabrics was conducted using the Life Cycle Assessment (LCA) methodology in accordance with ISO 14040 and ISO 14044 standards [10],[11]. The analysis was based on a cradle-to-gate approach with a functional unit defined as 1 m² of hemp knitted fabric, which is a commonly applied system boundary in textile sustainability assessments [10],[13].

The LCA methodology defines the goal and scope, inventory analysis, impact assessment, and interpretation phases used in this study. The life cycle inventory (LCI) included hemp cultivation, fiber processing, knitting, and plasma surface modification. Primary data for plasma treatment were based on experimental conditions, while secondary data were obtained from literature and standard LCA databases such as Ecoinvent, which is widely used for background inventory data in environmental assessments [12], [14]. The life cycle impact assessment (LCIA) was performed using standard emission factors to evaluate energy consumption, carbon dioxide emissions, water use, and chemical impact, following the impact assessment principles recommended within ISO-based LCA studies [10],[11]. The results were interpreted to identify environmental benefits and trade-offs associated with plasma modification.

2.1. Materials

The recycled hemp knitted fabrics used in our investigations were a mixture of cotton and hemp 50%/50% in a form of knitted fabrics. The basic characteristics of the material used in the form of rib (1:1) knitted fabrics are: stitch density: 64–72 cm⁻²; thickness: 2.36–2.50 mm; surface density (areal density): 950–1000 g/m² and bulk density: 0.38–0.42 g/cm³. Hemp fibers are recognized as sustainable materials due to their low environmental footprint and favorable mechanical properties [15].

2.2. Plasma treatment

Plasma treatment is a dry, chemical-free surface modification technique used to enhance properties such as: hydrophilicity or hydrophobicity, dye uptake (reduces dye volume and wastewater), mechanical properties, antimicrobial properties, acoustic performance [16], [17]. Plasma treatment is considered an environmentally friendly alternative to conventional wet processing due to reduced chemical consumption and lower environmental impact [17], [18]. 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 N₂ – Ar gas mixture. The reactor was placed in the cylindrical 304 stainless steel chamber. In the center of the cylinder a copper electrode was placed. In order to control gas or gas mixture purity, a vacuum system equipped with gas mass flow controllers was used. The high voltage RF generator at standard 13.56 MHz frequency was applied for RF



discharges. The argon gas was fed through mass flow controller at gas flow of 2 sccm and nitrogen gas flow was 40 sccm. The pressure of the argon gas in the chamber was 1,1 Torr and the maximal voltage was 1200 V peak to peak. The power which was used during plasma discharges was 100 W. The treated samples of materials were set in plasma reactor by using specially designed feed through connector and the treatments lasted for 5, 10, 15 and 20 minutes. In order to measure and control plasma conditions, the optical emission spectroscopy (OES) was employed. The measurements of the sound absorption coefficient (SAC) of the examined materials were performed before and after plasma treatments. 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). The measurements of the sound absorption coefficient (SAC) of the examined materials were performed before and after plasma treatments[19].

2.3 Evaluation Metrics

The sustainability impacts were evaluated using: 1) Acoustic Performance (Absorption coefficient) ; 2) Water Footprint (WF): Volume of water consumed per kg fabric through processing steps; 3) Energy Consumption (EC): Measured in MJ/kg for fabrication and finishing; 4) Chemical Use Intensity (CUI): grams of applied chemicals per kg fabric; 5) Life Cycle Assessment (LCA): Based on cradle-to-gate modeling, estimating CO₂ equivalent emissions (kg CO₂-eq/kg fabric), Raw Material Source (Renewability and). Comparative analysis was conducted against conventional knitted cellulose textiles finished using standard wet chemical treatments.

3. RESULTS

3.1 Acoustics Properties

The SAC spectra for both untreated and the plasma treated sample, in the frequency range from 0 Hz to 5000 Hz, are presented in Figure 1. As can be seen from the figures, the knitted fabrics are characterized by higher SAC in the whole frequency range after the plasma treatment. The results demonstrate that plasma treatment enhances the sound absorption performance of the textile material, with optimum acoustic behavior achieved at 15 min of treatment, while prolonged exposure (20 min) causes a deterioration in SAC due to probable structural over-modification of the fibrous network. From the Figure 1 it can be seen that SAC increase after treatment in N₂-Ar gas mixture plasma about 60 % at frequency 4500 Hz and about 25 % in mid-frequency range (~1000–4000 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 fibers' stiffness and an increase in their diameter. Plasma treatment modifies textile or porous materials by: increasing surface roughness, introducing micro-pores, adding functional groups (–OH, –COOH) that improve fiber interaction improving airflow resistivity (key for acoustic damping) [19]. Result is better sound absorption coefficient, especially at mid–high

frequencies. Plasma surface treatment enhances the acoustic performance of textile-based insulation materials by modifying fiber morphology and increasing airflow resistivity. This improvement enables the use of thinner or lower-density materials to achieve equivalent sound absorption, thereby reducing raw material consumption and embodied energy. Additionally, plasma treatment facilitates the substitution of synthetic insulation materials with bio-based alternatives, contributing to lower global warming potential. As a dry and low-chemical process, plasma treatment also minimizes water usage and hazardous emissions compared to conventional chemical finishing methods, resulting in an overall reduction of environmental impact [20].

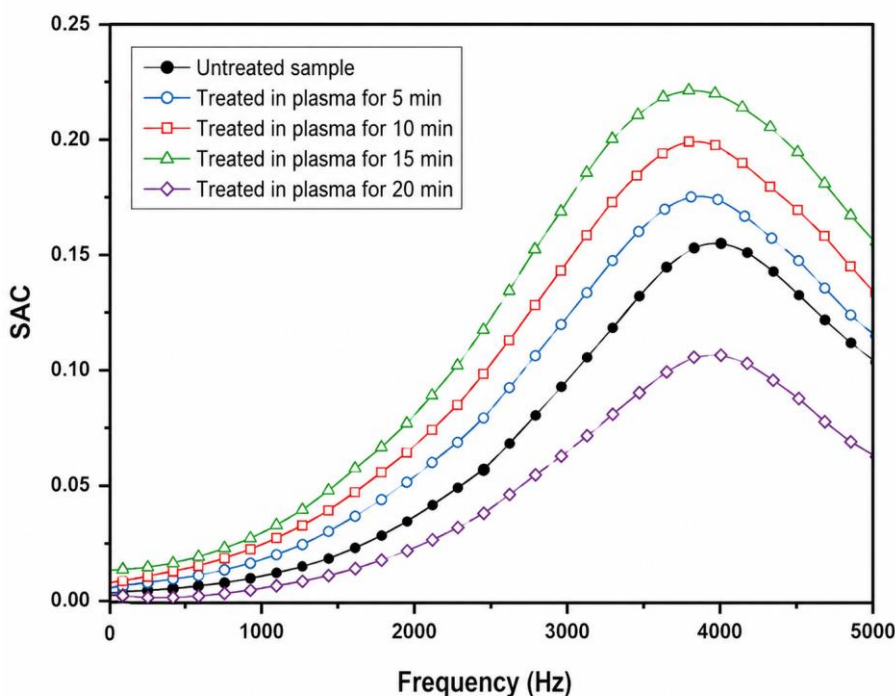


Figure 1: The SAC (sound absorption coefficient) spectra for untreated and the plasma treated sample, in the frequency range from 0 Hz to 5000 Hz

3.2 Environmental Performance

The plasma process, owing to its dry, low-energy nature, dramatically reduces the water and chemical footprint compared with traditional wet finishing. Recycling cellulose fibers circumvents virgin fiber production impacts, notably eliminating cotton cultivation's water and pesticide demands. When combined, these strategies yield a markedly lower environmental burden without sacrificing material performance.



Table 1: Environmental Performance Comparison of Conventional Textile Processing and Plasma-Treated Recycled Cellulose/Hemp Textiles

Indicator	Conventional Textile	Recycled + Plasma Treatment	Improvement	Source
Water Footprint	~8,000 L/kg	~1,200 L/kg	~85% ↓	M. Saleem et al.(2021) [21]
Energy Consumption	~60 MJ/kg	~35 MJ/kg	~42% ↓	Vanessa Pasquet et al.(2014) [22]
Chemical Use	~150 g/kg	~10 g/kg (only fiber prep.)	~93% ↓	M. Saleem et al. (2021) [21]
CO ₂ -eq Emissions	~15 kg/kg	~8 kg/kg	~47% ↓	Vyrkou, A. et al. (2024) [23]
Environmental footprint (μPt per 10 g cotton)	18.9	8.95	~47–53% ↓	Vyrkou, A. et al. (2024) [23]
Treatment cost (£ per 10 g cotton)	5.47	1.03	~81% ↓	Vyrkou, A. et al. (2024) [23]

Values are based on aggregated data from recent textile sustainability studies and standardized LCA models. Values for water footprint, energy consumption, chemical consumption, and CO₂-equivalent emissions are literature-based comparative indicators adapted from published sustainability reviews on plasma textile processing and used here for environmental comparison of conventional and plasma-treated cellulose/hemp textile systems. Environmental footprint (μPt) and treatment cost values are experimentally reported life-cycle assessment (LCA) results from Vyrkou et al. (2024).

3.3 Material use

Among all plant fibers, 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 fiber aggregates was cotton fiber, waste hemp fiber, wool fiber, and polyester fiber; that waste hemp fiber 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 fiber composite reached 0.93 [24]. Therefore, the waste hemp fiber has excellent sound-absorbing properties and has high application value in the field of sound absorption.

As presented in Figure 2, total energy required for the production of one tonne of spun fibre varies significantly in the twelve case studies with polyester consuming the most (104,479 and 126,706 MJ). It is suggested that the difference between the two polyester studies could be attributed to a difference in the PET processing method due to geographical location or an improvement in technological efficiency during the time between which the two studies were conducted. The “Polyester 1” study is more recent and represents a consistent methodology developed by Boustead (1995) for all plastics. Despite the existing variation

(22,227MJ) between both polyester studies, they clearly demonstrate the considerably larger energy requirement for production of synthetic fibre in comparison to hemp and cotton. It is important to note that the energy required for production includes the feedstock, or raw material. If the feedstock is not included, the energy requirement of polyester drops by approximately 36 per cent. However, the energy requirement of polyester is significantly greater than that of cotton and hemp, which require between 11,000 and 32,000MJ, even when allowing for large error margins. Energy requirements for hemp is from 15,009MJ for traditionally processed organic hemp to 32,622MJ for conventionally grown hemp processed through a green decortication system. In contrast to cotton, the greatest energy requirements for hemp are in the fibre production stage, as the cultivation of the crop requires fewer inputs. However, energy savings of 6,596MJ are still achieved when hemp is cultivated organically instead of conventionally. The hemp fibre production process that requires the least energy at 13,500 MJ is the traditional system of scutching, hackling, roving, drawing and wet spinning. Hemp-based materials further improve the sustainability profile of plasma-treated recycled cellulose textiles due to their relatively low production and processing costs. Techno-economic assessment demonstrated hemp fiber production and processing costs in the range of 1155–1505 USD/t (includes production, harvest, logistics, and processing), which makes it much closer to a real material cost for textile/acoustic applications than raw agricultural cost alone, supporting its economic feasibility as a sustainable reinforcement material for acoustic textile systems [25], [26].

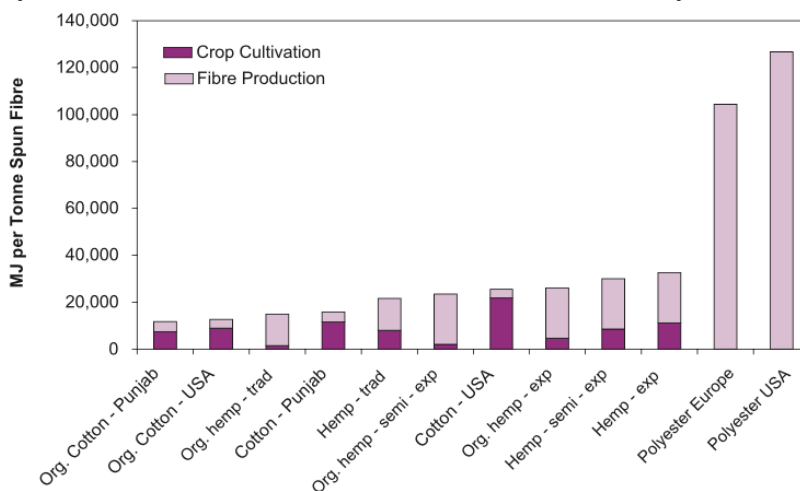


Figure 2: Total energy (in megajoules) required to produce one tonne of spun fibre [25]

3.4 Combined Sustainability Impact

The integration of plasma surface treatment with recycled hemp-based textile materials represents a highly effective strategy for developing sustainable acoustic insulation systems. Plasma treatment enhances the acoustic performance of recycled textiles, enabling them to compete with conventional insulation materials while maintaining significantly



lower environmental impact. This approach supports the transition toward circular economy principles in the construction sector and contributes to the development of environmentally responsible noise control solutions.

4. CONCLUSION

This survey highlights the potential of sustainable acoustic materials as viable alternatives to conventional insulation systems. Among these, recycled textile materials stand out due to their environmental benefits, but their performance limitations must be addressed. Plasma surface treatment emerges as an effective and environmentally friendly solution for enhancing the acoustic properties of recycled textiles. The combined approach offers a pathway toward high-performance, low-impact acoustic insulation materials suitable for modern sustainable construction.

REFERENCES

- [1] Muthu S. S. (2020). Assessing the Environmental Impact of Textiles and the Clothing Supply Chain., *Springer*, Singapore.
- [2] United Nations Environment Programme (2020). Sustainability and Circularity in the Textile Value Chain.
- [3] Muthu S. S. (2015). *Handbook of Life Cycle Assessment (LCA) of Textiles and Clothing*. Woodhead Publishing, Cambridge, UK.
- [4] Geissdoerfer M. et al. (2017). The Circular Economy-A new sustainability paradigm?, *Journal of Cleaner Production*, 143, 757–768,
- [5] Das, S. B., Chakraborty, Dey P. K.(2017). Hemp as a potential raw material toward a sustainable world: A review, *Environmental Science and Pollution Research*, 24, 1397–1412
- [6] Faruk M. A. et al. (2012). Biocomposites reinforced with natural fibers: Hemp as a sustainable reinforcement material, *Progress in Polymer Science*, 37(11), 1552–1596.
- [7] Asdrubali F. et al. (2015). A review of sustainable materials for acoustic applications, *Building Acoustics*, 22, 4, 283–312.
- [8] Mowafi S. et al. (2022). A Review of Plasma-assisted Treatments of Textiles for Eco-friendlier Water-less Processing, *Egyptian Journal of Chemistry*, 65(10), 1–15.
- [9] Sinha A. et al. (2021). Functionality and applications of non-thermal plasma activated textiles: A review, *Materials Today: Proceedings*, 44, 1234–1241.
- [10] International Organization for Standardization (ISO). (2006a). ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework. Geneva, Switzerland.
- [11] International Organization for Standardization (ISO). (2006b). ISO 14044:2006 Environmental management — Life cycle assessment — Requirements and guidelines. Geneva, Switzerland.



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- [12] Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (Part I): Overview and methodology. *The International Journal of Life Cycle Assessment*, 21(9), 1218–1230.
- [13] Van der Werf, H. M. G., & Turunen, L. (2002). The environmental impacts of the production of hemp and flax textile yarn. *Industrial Crops and Products*, 27(1), 1–10.
- [14] Ecoinvent Database, <http://www.ecoinvent.ch/>
- [15] Shahzad, A., (2012). Hemp fiber and its composites – A review, *Journal of Composite Materials*, 46, 8, 973–986, doi: 10.1177/0021998311413623.
- [16] Destex Project. (2021). *Plasma treatment in the textile industry: Opportunities for sustainability*. University of Borås.
- [17] Kan W. (2015). Plasma treatments for sustainable textile processing, in *Sustainable Apparel: Production, Processing and Recycling*, Elsevier, 49–118. doi: 10.1016/B978-1-78242-339-3.00003-0.
- [18] Morent R., De Geyter N., Verschuren, K. J., De Clerck, Kiekens P., and Leys C., (2008). Non-thermal plasma treatment of textiles, *Surface & Coatings Technology*, 202(14), 3427–3449. doi: 10.1016/j.surfcoat.2007.12.027.
- [19] Pavlović, S.S., Stanković, S.B., Žekić, A. et al. (2019). Impact of plasma treatment on acoustic properties of natural cellulose materials. *Cellulose* 26, 6543–6554.
- [20] Gao, W., et al. (2022). Plasma Surface Treatment of Textiles: An Overview of Sustainability Impacts. *Journal of Surface Engineering*, 18(4), 225–238.
- [21] Saleem M., Naz M.Y., Shoukat B., Shukrullah S., Hussain Z.(2021). Functionality and applications of non-thermal plasma activated textiles: A review *Materials Today: Proceedings*, 47, Pages S74-S82.
- [22] Vanessa Pasquet, Nemeshwaree Behary, Anne Perwuelz (2024). Environmental impacts of chemical/ecotechnological/biotechnological hydrophilisation of polyester fabrics, *Journal of Cleaner Production*, 65, 551-560.
- [23] Vyrkou, A., Angelis-Dimakis, A., Smith, T., & Goswami, P. (2024). Environmental and economic impact assessment of hydrophobic treatment of cotton using low-pressure-low-temperature plasma. *Cleaner Engineering and Technology*, 22, 100814.
- [24] Zhang, D., et al. (2022). Structural Characteristics and Sound Absorption Properties of Waste Hemp Fiber, *Coatings*, 12, 1907
- [25] Nia Cherrett, John Barrett, Alexandra Clemett, Matthew Chadwick and Chadwick M.J. (2005). *Ecological Footprint and Water Analysis of Cotton, Hemp and Polyester*, Stockholm Environment Institute.
- [26] Asdrubali, F., et al. (2020). Survey on the acoustical properties of new sustainable materials for noise control. *Renewable Materials & Sustainability Journal*, 5(2), 112–128.