Journal of Environmental Management 363 (2024) 121363

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Upcycling of industrial footwear waste into nonwoven fibrous structures with thermal and acoustic insulation properties

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A R T I C L E I N F O

Keywords:
Acoustic insulation
Industrial footwear waste
Nonwoven structures
Polyester
Tensile resistance
Thermal insulation

A B S T R A C T

The footwear industry significantly impacts the environment, from raw material extraction to waste disposal. Transforming waste into new products is a viable option to mitigate the environmental consequences, reducing the reliance on virgin raw materials. This work aims to develop thermal and acoustic insulation materials using polyester waste from footwear industry. Two nonwoven and two compressed nonwoven structures, comprising 80% polyester waste and 20% commercial recycled polyester (matrix), were produced. The materials were created through needle-punching and compression molding techniques. The study included the production of sandwich and monolayer nonwoven structures, which were evaluated considering area weight, thickness, air permeability, mechanical properties, morphology using field emission scanning electron microscopy, and thermal and acoustic properties. The nonwoven samples presented high tensile strength (893 kPa and 629 kPa) and the highest strain (79.7% and 73.3%) and compressed nonwoven structures showed higher tensile strength (2700 kPa and 1291 kPa) but reduced strain (25.8% and 40.8%). Nonwoven samples showed thermal conductivity of 0.041 W/K.m and 0.037 W/K.m. Compressed nonwoven samples had higher values at 0.060 W/K.m and 0.070 W/K.m. While the sample with the highest conductivity exceeds typical insulation levels, other samples are suitable for thermal insulation. Nonwoven structures exhibited good absorption coefficients (0.640–0.644), suitable for acoustic insulation. Compressed nonwoven structures had lower values (0.291–0.536), unsuitable for this purpose. In summary, this study underscores the potential of 100% recycled polyester structures derived from footwear and textile industry waste, showcasing remarkable acoustic and thermal insulation properties ideal for the construction sector.

1. Introduction

The global production of municipal solid waste reaches 2.01 billion tonnes, with at least 33 % of it not being appropriately handled in an environmentally sustainable manner (Kaza et al., 2018). In 2022, the largest landfill sites worldwide experienced a daily influx of 10 thousand tons of waste, a trend that has been persistently escalating in recent decades with no signs of slowing down (Alves, 2023; Valavanidis, 2023). Among this waste, it is approximated that clothing and textiles presently constitute a minimum of 7% of the total volume in global landfill sites (Ruiz, 2023). More precisely, in the context of the footwear industry, manufacturing has consistently expanded year after year, reaching a cumulative production of 23 billion pairs of shoes annually (Portuguese shoes, 2023; Staikos and Rahimifard, 2007; Van Rensburg et al., 2020). This stands in contrast to the disposal of 22 billion pairs of shoes per year in landfills (Dennis, 2022). The extensive scale of production and consumption results in an increase in waste generation, adversely affecting the environment and human health. Large quantities of waste, when decomposed in landfills, significantly contribute to environmental pollution, contaminating groundwater and generating greenhouse gases during decomposition (Baccouch et al., 2022; Dissanayake et al., 2018; Islam and Bhat, 2019). Textile waste can be particularly harmful since it may have absorbed various heavy metals during production, which can damage the environment when disposed of in a landfill (Dev et al., 2022;

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https://doi.org/10.1016/j.jenvman.2024.121363
Received 6 February 2024; Received in revised form 14 May 2024; Accepted 31 May 2024
Available online 7 June 2024
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Krishnan et al., 2017; Shiny Raj and Anoop Krishnan, 2023). Effective waste management is crucial to minimize environmental impact. The best strategies for reducing textile waste involve avoidance, reduction, and reuse. However, the adoption of these practices depends on societal awareness, which is currently lacking. The prevailing consumption pattern in society, known as "fast fashion," stands as the primary factor driving this surge. It reduces prices but compels consumers to purchase products unnecessarily (Bukhari et al., 2018; Islam and Bhat, 2019; Staikos and Rahimifard, 2007). At the end of a product's life cycle, various approaches can be considered, including recycling, incineration, biodegradation, and landfill (Muthu, 2020). Recycling is the optimal choice as it reduces water and energy consumption by replacing virgin raw materials with recycled ones, thus preventing the depletion of non-renewable resources (Baccouch et al., 2022; Muthu, 2020).

Currently, textile waste is managed through unplanned methods such as incineration (using pyrolysis and gasification for power and heat) or landfilling (utilizing hydrolysis for decomposition into monomers, fuels, and chemicals). These practices contribute to environmental pollution, leading to contaminants in soil, air and water (Mishra et al., 2022; Muthu, 2020; Rapsikevičienė et al., 2019). To address this issue, various valorization methods are employed, including mechanical and chemical processing for conversion into textiles, packaging film and paper. Additionally, melt processing is utilized for composites, while composting transforms waste into composts and bio-manures, among other applications (Bhatia et al., 2014; Mishra et al., 2022; Patti et al., 2020). Textile waste is commonly recycled by transforming it into thermal and acoustic insulation materials through the production of nonwoven structures and composites (Bhatia et al., 2014; Hadded et al., 2016; Islam and Bhat, 2019; Venkataraman et al., 2023). The conversion process is varied, as there are various types of waste, such as industrial waste, post-consumer waste, synthetic waste, natural waste, among others (Bhatia et al., 2014; Islam and Bhat, 2019). Nonwoven structures are unique structures consisting of a skeleton of dense and porous fibers, making them ideal materials for thermal and acoustic insulation applications. In some cases, nonwoven materials may undergo high heat and compression molding to produce composite materials (Islam and Bhat, 2019; Wazna et al., 2019). Nonwoven structures, used in applications not requiring traditional garment assembly, offer cost advantages due to shorter production times (Venkataraman et al., 2023). Nonwoven structures find application in various fields such as aerospace, automotive, furniture, insulation, fire retardant materials, industrial filters, puncture-resistant materials, and more, generating new textile and non-textile products (Bhatia et al., 2014; Islam and Bhat, 2019; Venkataraman et al., 2023). Patnaik et al. developed several nonwoven structures for application as thermal and acoustic insulation, using wool and polyester waste (post-industrial waste), using the needle-punching method. The values obtained for thermal conductivity and sound absorption coefficient are between 0.030 and 0.038 W/mK and 0.340–0.580 (at 1000–2000 Hz), respectively (Patnaik et al., 2015). Using polyester, linen and cotton waste (post-industrial), Zach et al. also produced insulation structures for building construction. The average thermal conductivity and absorption coefficients of materials were 0.036–0.050 W/mk and 0.350 to 1.000, respectively (Zach et al., 2016). Trajkovic et al. produced two sandwich-shaped nonwoven structures, in which polyester waste (post-industrial waste) is wrapped in a polypropylene (PP) nonwoven structure. The structures presented good results for thermal (λ = 0.0520 and 0.0603 W/mK)) and acoustic insulation (α = 0.700–0.950 at 1000–2000 Hz) (Trajković et al., 2016). Using cotton and polyester selvedges, Bogale et al. have produced several nonwoven structures for application as insulation. The values obtained for thermal conductivity and sound absorption coefficient are between 0.130 and 0.170 W/mk and 0.050–0.290 (at 1000–2000 Hz), respectively (Bogale et al., 2023).

Composite materials can also be incorporated with waste for application in building construction (Islam and Bhat, 2019). Ricciardi et al. produced composites from industrial textile and paper waste, using glue as a binding agent. The thermal behavior is between 0.034 and 0.039 W/mK and the sound absorption coefficient varies in the 0.280–0.450 at 1000–1600 Hz (Ricciardi et al., 2014). It is also possible to produce composites from nonwoven structures. Lin et al. used kevlar, nylon, polyester and PP waste and produced nonwoven structures. Then, these structures were converted into composites by compression molding. The thermal conductivity of the materials were between 0.026 and 0.046 W/mK. The sound absorption coefficient were between 0.000 and 0.350 at 1000–2000 Hz. These values are low because in the compression molding process, the spacing between the fibers is reduced, which increases the stiffness of the composite and, consequently, a decrease in the absorption coefficient (Lin et al., 2016). Rubino et al. also recycled wool and polyester, first producing nonwoven structures, which were later converted into composites. The composite materials have good thermal (λ = 0.044–0.057 W/(m/K)) and acoustic properties (α = 0.700–1.000) for sustainable application in civil construction (Rubino et al., 2021).

Developing 100% recycled materials promotes a circular economy, where products and materials are reused and recycled at the end of their life cycle (Jørgensen and Pedersen, 2018; Neves and Marques, 2022). This contrasts with the linear model of "take, make, dispose," leading to a more sustainable and regenerative approach (Geisendorf and Pietrulla, 2018; Neves and Marques, 2022; Sariatli, 2017). This approach enables economic growth to be separated from the adverse impacts of resource depletion and environmental degradation (Jørgensen and Pedersen, 2018; Morseletto, 2020; Neves and Marques, 2022). Using recycled materials reduces the demand for new virgin materials. This helps conserve natural resources such as timber, water, and minerals, leading to a more sustainable use of the Earth's finite resources (European Parliament, 2023; Morseletto, 2020; Neves and Marques, 2022). By incorporating recycled materials into new products, the amount of waste sent to landfills is reduced. This is crucial for mitigating the environmental impact of landfills, which can produce harmful greenhouse gases and leach toxic substances into the soil and water (Kumar et al., 2021; Velasquez, 2011).

Converting textile waste into building insulation materials holds substantial promise for a multitude of advantages. The implementation of superior thermal and acoustic insulation materials has the potential to significantly reduce the negative impact on the environment, minimize the use of virgin fiber materials, minimize energy consumption, reduce the need for landfill space, reduce greenhouse gas emissions, and mitigate different types of pollution. This approach not only preserves petroleum, fuel, and natural resources but also enhances the overall well-being of human environments (Bhatia et al., 2014; Islam and Bhat, 2019). The recycling of textile waste into insulation materials is in harmony with circular economy principles, potentially establishing a novel market for these repurposed materials (Alves et al., 2024; Neves and Marques, 2022). Moreover, the production of economical thermal insulation materials has the potential to lower energy consumption for heating and cooling, benefiting both buildings and automotive applications (Bhatia et al., 2014; Islam and Bhat, 2019). Currently, prevalent building insulation materials are derived from synthetics like glass fiber, mineral wool, and plastics. Approximately 60% of building construction materials are estimated to come from mineral or inorganic fibrous materials, 30% from foam materials, and the remainder from non-traditional or composite materials (Ardente et al., 2008; Islam and Bhat, 2019; Patnaik et al., 2015). These materials have adverse environmental impacts as they are non-renewable and non-disposable. Some of them also pose health risks to individuals (Asdrubali et al., 2015; Islam and Bhat, 2019; Papadopoulos, 2005; Patnaik et al., 2015). Due to these negative effects, there is a need for new, environmentally friendly materials that are not harmful to people's health. Natural materials such as flax, straw, corn, reed, bamboo, banana fibers, and pineapple fiber are utilized for thermal and acoustic insulation in construction, though their adoption remains limited, yet steadily increasing, especially in sustainable and eco-friendly building projects (Cosentino et al., 2023; Raja et al., 2023).

The objective of this study is to produce nonwoven structures by incorporating footwear polyester waste through the needle-punching method as a material for acoustic and thermal insulation in building construction. By using this material, this approach innovates since it reduces the need for new raw materials, energy consumption, and the environmental footprint associated with traditional manufacturing processes. This approach also aligns with the principles of a circular economy, where instead of following a linear "take, make, dispose" model, it promotes a closed loop where materials are reused and recycled, contributing to a more sustainable and eco-friendly manufacturing process. Subsequently, the nonwoven materials underwent treatment involving high temperature and pressure to create compressed nonwoven structures. This article provides insights into the characterization, manufacturing process, and the mechanical, thermal, and acoustic properties of these compounds and how they compare to commonly used materials.

2. Materials and methods

2.1. Polyester waste grinding

The polyester waste (Fig. 1A) used in this work comes from AMF Safety Shoes Company, a safety footwear production industry in Portugal. These residues are leftovers from the production process (post-industrial waste). Polyester waste was ground in a cutting mill, S200 Retsch equipment (Fig. 1B), using a 1*1 cm square sieve, and the residues underwent two milling cycles. The milled polyester had a final length between 1 mm and 16 mm, measured using a stereo microscope Leica EZ4 D (Fig. 1C–D). An Ultra-high-resolution Field Emission Scanning Electron Microscopy (FESEM), NOVA 200 Nano SEM, FEI Company (Hillsboro, OR, USA), was used for measuring the diameters of the fibers, displaying an average diameter of 27.94 μm (Fig. 1E).

2.2. Characterization of polyester waste

Polyester waste was characterized by attenuated total reflectance-Fourier transform infrared spectroscopy (ATR-FTIR) and thermogravimetric analysis (TGA). ATR-FTIR spectroscopy studies were performed with IRAffinity-1S, SHIMADZU equipment. Each spectrum was acquired in transmittance mode on a diamond ATR crystal cell by accumulation of 45 scans with a resolution of 8 cm^{-1} from 4000 to 380 cm^{-1}. TGA was carried out on a STA 700 SCANSCI. The TGA trace was obtained in the range of 30–600 °C, under nitrogen atmosphere, with a flow rate of 200 mL/min and heating rate of 10 °C/min.

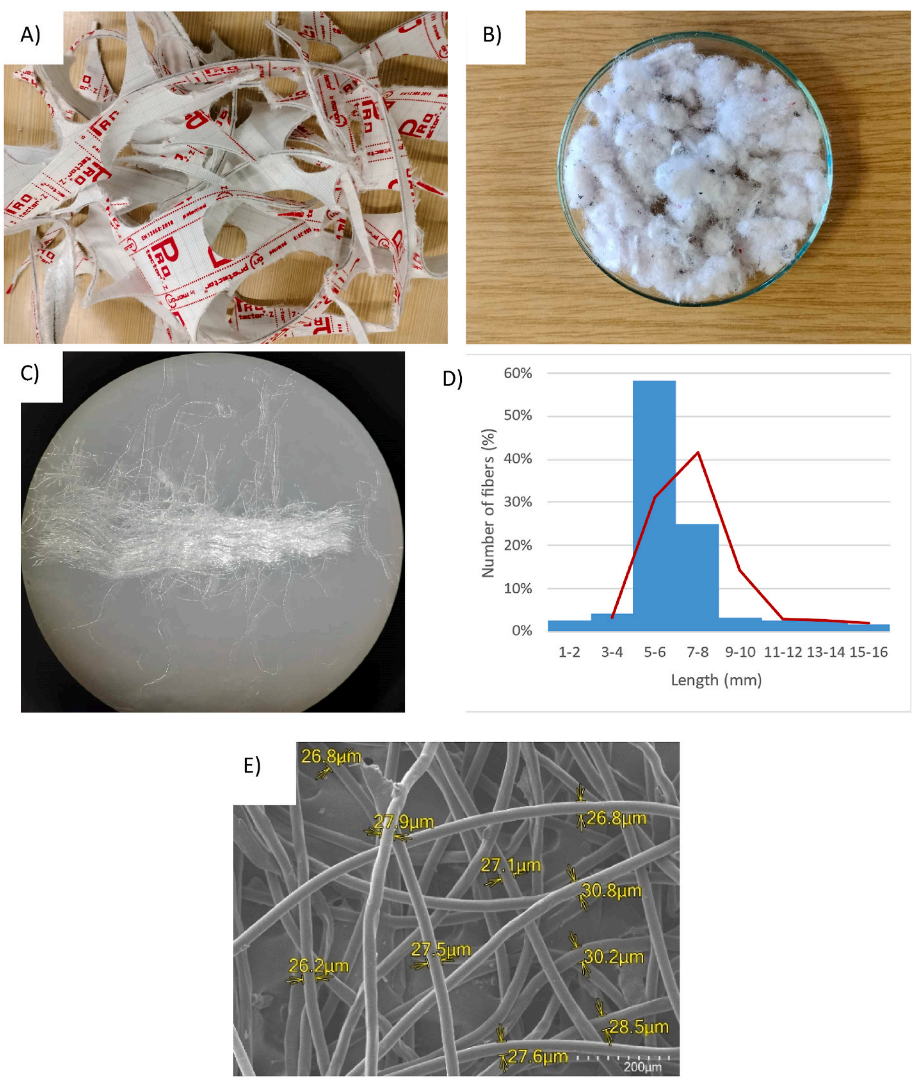

Fig. 1. Polyester waste from footwear recycling. A) Before grinding; B) After grinding; C) Stereo microscope image; D) Fiber lengths histogram; E) SEM image of the polyester waste with diameters.

2.3. Nonwoven structures production

To produce nonwoven structures, the incorporation of an additional material as a matrix was essential due to the exceedingly small diameters (27.94 μm) and length (6–15 mm) of the polyester waste fibers. To maintain the concept of circular economy of the mat, commercial recycled polyester (from textile industry) was used as the matrix. To produce the nonwoven structures, the needle-punching method was followed and the Cosmatex© Construzione Macchine Tessili machine, type Linea Campioni HL 500, was used. This machine is connected to the needling machine, forming the Automatex© Needling Nonwovens Production Line. This method does not resort to chemical agents for bonding, because the fiber connection is made through the needles (Maity et al., 2012).

For the sample's preparation, initially, fibers were opened and introduced into the card stage, in which they were arranged in the form of a fibrous web with the fibers randomly oriented. The thickness of the web was controlled by means of a cross lapper. Finally, the fibrous web undergoes through a plate of needles, where they are consolidated by the repeated insertion of barbed needles. The strokes were set at 400/min. This procedure enhances the cohesion of the fibrous web by interlocking its fibers, all without the use of any binding agent (Maity et al., 2012). Within this method, there are two techniques for producing nonwoven structures: the sandwich and monolayer technique as can be seen in Fig. 2. In the monolayer technique (Fig. 2A), the polyester waste are mixed with the matrix before the carding process, being incorporated directly into the mat at the end. The final sample is only composed by 1 layer.

In the sandwich technique (Fig. 2B), a mat is produced with only the fibers of the matrix. Then the polyester waste is added to the first mat and covered again with another layer of the same mat. This nonwoven structure is composed of 3 layers, the inner layer being formed by the polyester waste.

All parameters for nonwoven production were kept same for all samples (A and B). One sample was produced for each technique. The major goal of this work was to maximize the quantity of waste incorporated in the nonwoven structures, so numerous polyester waste percentages were included in them: 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100%. To determine the optimal structure, numerous characteristics were considered: mass loss during the manufacturing process, visual aspect, physical integrity, and mechanical properties. After examining these factors, the sample with 80% polyester waste was deemed the best.

Samples A and B underwent compressed molding at 10 kN and 250 °C for 4 min using a LabManual300 - Fontijne Presses, resulting in the creation of compressed nonwoven structures C and D as depicted in Fig. 2C–D, respectively. Table 1 displays the physical characteristics of the four samples.

2.4. Area weight, thickness and air permeability

The area weight is defined as the mass per unit area and was

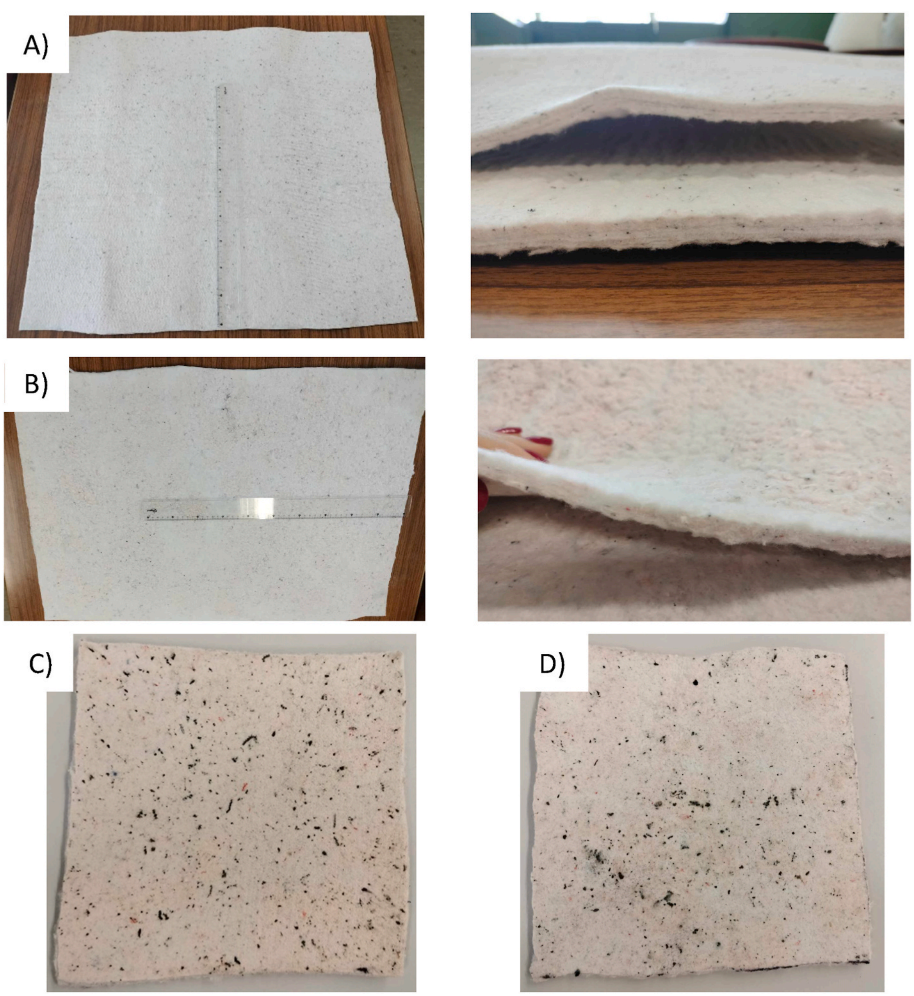

Fig. 2. Nonwoven structures produced incorporated with 80% polyester waste. A) Monolayer method. B) Sandwich method. C) Compressed nonwoven structure (from sample A). D) Compressed nonwoven structure (from sample B).

Table 1
Sample composition.

Sample code	Technique	% Matrix	% Polyester waste	Number of layers
A	Monolayer	20	80	1
B	Sandwich	20	80	3
C	Compression molding	20	80	1
D	Compression molding	20	80	1

measured according to ISO 9073–1:2023 (ISO, 2023a). The measurement was carried out on three random samples of each nonwoven structure, using an electronic balance. It measured in g/m^2. The thickness of the mats were measured according to IS0 9073–4 (ISO, 1989). Ten random readings were taken from each sample for measuring thickness.

Air permeability, the velocity of air flow that passes perpendicularly through a given area of nonwoven structure in a given period of time, was evaluated according to the ISO 9237:1995 standard (ISO, 1997). The tests were carried out on TEXTEST FX 3300, using a pressure indicator of 200 Pa. Air permeability is given in l/m^2/s. Ten random tests were carried out for each sample, in a circular format of 20 cm^2.

2.5. Mechanical properties

Tensile testing was carried out on a Mecmesin MultiTest-I with a 10 KN load cell. For samples A and B, the ISO 9073-3 standard was followed (ISO, 2023b). The width and length of the samples were 5 cm and 25 cm, respectively, and the gauged length was 20 cm. For samples C and D, ASTM D3039 standard was followed (ASTM, 2017). The samples were 1 and 7.5 cm width and length, respectively, with a gauged length of 5 cm. The long dimension was parallel to the direction of testing and force application. Five tests were performed for each sample, and the results were reported by calculating the average strain and tensile strength.

2.6. Field emission scanning electron microscopy

The morphological analysis of the samples was performed in an Ultra-high-resolution Field Emission Scanning Electron Microscopy, NOVA 200 Nano SEM, FEI Company (Hillsboro, OR, USA). Before the analysis, the samples were covered with a very thin film (20 nm) of Au–Pd (80–20 wt %), using a high-resolution sputter coater, 208 HR Cressington Company (Watford, UK), coupled to an MTM-20 Cressington High Resolution Thickness Controller. Secondary electron images, i. e., topographic images, were performed at an acceleration voltage of 10 kV.

2.7. Thermal properties

The thermal conductivity (λ) of a material is defined as the amount of heat crossing a unit area of the material per unit time per unit temperature gradient. The thermal resistance is expressed by the relationship between thickness and thermal conductivity (Mishra et al., 2019). These two properties were studied using the guarded hotbox method, according to the ISO 9869:1994 standard (ISO, 1994). The hotbox method consists of two chambers, one of the chambers is heated and the energy flow is measured while the second chamber is maintained at the lower temperature. The temperature difference between the hot side (34 °C) and the cold side (19 °C) is set at 15 °C in all measurements. Three tests were carried out during 72 h for each of the samples. Each sample was 15*15 cm. For this test, the portable measurement system, green TEG's gOMS II, was used.

2.8. Acoustic properties

The sound absorption coefficient (α) was determined following ISO 10534-2 standards (ISO, 1998). Measurements were conducted using a custom-made Kundt impedance tube (80 mm diameter, 410 mm inner length) with a probe positioned at 48 mm. The setup included an 8 Ω Speaker, a Microflown probe, an MFPA-2 preamplifier, a Scout 442 amplifier, and a Microflown digital frequency analyzer. Samples were tested in 120 mm diameter circles. The frequency range used for the measurement was 300–2000 Hz. Two classes of frequencies were analyzed, low (up to 500 Hz) and medium frequencies (500–2000 Hz). Five readings were taken randomly from each sample for evaluating acoustic properties. A commercially available acoustic isolation material made out of polyurethane was used as a control sample for result comparison.

3. Results and discussion

3.1. Polyester waste characterization

The polyester waste from footwear industry was analyzed as received. The ATR-FTIR spectrum obtained for polyester waste (Fig. 3A) reflects the typical behavior of a pure polyester spectrum (Vahur et al., 2016). The intense bands at 1715 and 1092 cm^{-1} correspond to the carbonyl group and the hydroxyl group, respectively. The stretching vibrations of the CH and CC bonds of the benzene rings appear at 2961 (weak), 870 (weak) and 717 (strong) cm^{-1}. The TGA also revealed typical behavior of a pure polyester sample (Bouazizi et al., 2018), with a loss of around 80% of mass between 375 °C and 475 °C (Fig. 3B). The

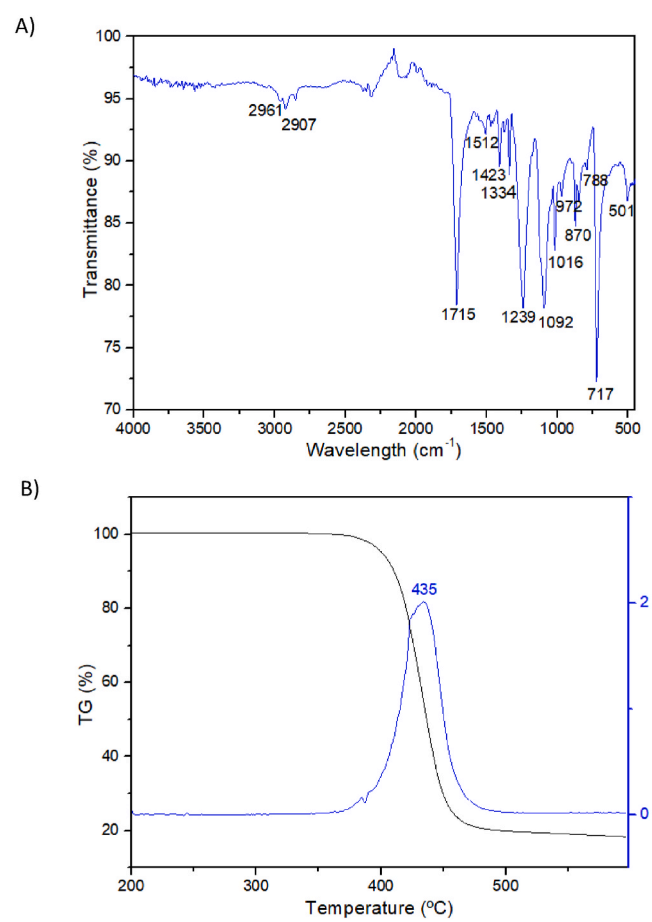

Fig. 3. Characterization of polyester waste. A) ATR-FTIR spectrum; B) TGA e DTG spectrum.

main peak at 435 °C corresponds to the maximum rate of thermal degradation.

3.2. Area weight, thickness and air permeability

Physical properties and air permeability of samples are shown in Table 2. Area weight and bulk density increased in samples C and D compared to A and B due to compression during manufacturing. The compressed samples had the same weight distributed over less volume, leading to higher area weight and bulk density, as indicated by decreased thickness. Bulk density values of samples A and B are comparable to traditional insulation materials (0.016–0.20 g/cm^3), while samples C and D are higher (Wazna et al., 2019). The study of air permeability is important for the thermal and acoustic insulation of buildings, as it is important to limit air flows and energy waste (Stanković et al., 2008). The air permeability values are much higher for samples A and B, as they were not compressed molding and, therefore, are more porous samples. Sample B has a lower permeability value when compared to A, due to its layered structure. As such, sample D (manufactured from sample B) has a lower permeability value when compared to C (manufactured from sample A), due to their manufacture from the previous samples.

3.3. Mechanical properties

The tensile strength and respective strain values obtained for the samples are represented in Table 3. Sample C displayed the highest tensile strength (2700 kPa), followed by sample D (1291 kPa). This may be related to the compression process, which most likely promotes fiber entanglement and alignment, improving structural integrity and making the material more resistant to stretching or tearing. On the other hand, sample A exhibited the highest strain (79.7%) followed by sample B (73.3%). These findings could be explained by the fact that nonwoven structures have looser fiber arrangements and less fiber alignment, allowing for greater flexibility and deformation under stress, resulting in higher strain before failure occurs. Compared to a commercial product like rock wool (with a tensile strength of 20 kPa), the developed products exhibit much higher tensile strength, making them mechanically more suitable for building construction.

3.4. Field emission scanning electron microscopy

SEM images of the surface and cross-section of samples A and B are represented in Figs. 4 and 5, respectively. The surface morphology of samples A and B is not uniform, with a large disorganization of the fibers, typical behavior of nonwoven structures (Islam and Bhat, 2019). It can also be seen that both samples are quite porous, which is beneficial for thermal and acoustic insulation properties (Cao et al., 2018). Analyzing only the surface of the samples, it was not possible to distinguish the two types of polyesters present. In sample A, because the fibers are randomly mixed during manufacture, no layers form, making it impossible to discern between the two fiber types in the cross-section (Fig. 5A). In sample B, the presence of three separate layers in the cross-section of sample B is visible due to the structure's layer production. Layers B1 and B3 are the exterior layers, made out of commercially recycled polyester matrix and layer B2 is dense and represents the polyester waste from the footwear (Fig. 5B). The existence of several layers contributes positively to the thermal and acoustic properties of the samples, as seen in above (Kurra, 2012; Matusiak and Kowalczyk, 2014).

Table 2
Physical properties and air permeability of samples.

Sample	Thickness (mm)	Area weight (g/cm^2)	Bulk density (g/cm^3)	Air permeability [l* (m^2/s)]
A	10	0.16	0.16	350
B	10	0.14	0.14	222
C	5	0.24	0.47	46
D	6	0.25	0.42	20

Table 3
Mechanical properties of samples.

Sample	Strain (%)	Tensile Strength (kPa)
A	79.7	893
B	73.3	629
C	25.8	2700
D	40.8	1291

3.5. Thermal properties

The thermal properties of the samples and reference values from the literature are represented in Table 4. Low values of the thermal conductivity imply higher resistance to heat conduction through the material. The barrier created by the material with low thermal conductivity prevents the high temperature flow. The thermal conductivity values of samples A and B are within the range of values for other nonwoven structures and commercial insulation materials (0.020–0.068 W/K.m) (Wazna et al., 2019). Sample B has slightly lower thermal conductivity than sample A, which can be justified due to its layered structure which provides better thermal properties because air has to permeate more layers. Samples C and D have higher thermal conductivity than samples A and B. This could be due to the fact that in compression molding the samples are pressed, reducing their porosity. Yet, sample C can be used in thermal isolation but sample D already exceeds this values, and thus cannot be used as an alternative to traditional isolation materials. These findings align with existing literature on the relationship between thermal properties and material characteristics. Despite samples A and B having greater thickness than C and D, which would typically enhance their conductivity, results remain consistent with this observed variance (Yang et al., 2020), the greater air permeability they possess exerts a more significant influence, leading to a decrease in conductivity (Duran, 2016).

When juxtaposing the values of samples A and B with those of other nonwoven structures, it is evident that they align within a similar range as observed in previous studies (Bogale et al., 2023; Patnaik et al., 2015; Trajković et al., 2016; Zach et al., 2016). Notably, Patnaik et al. achieved superior thermal conductivity (0.030 W/K.m) with a substantially lower value (Patnaik et al., 2015). In the domain of composites (Lin et al., 2016; Ricciardi et al., 2014; Rubino et al., 2021), samples A and B demonstrate comparable performance, although Lin et al. achieved a lower thermal conductivity value (0.026 W/K.m) (Lin et al., 2016). When benchmarked against commercial products, samples A and B exhibit values within the same range, affirming their potential as viable substitutes in terms of thermal conductivity for building construction. On the contrary, samples C and D surpass the values presented in most articles, indicating that they may not be as effective and might not be suitable for our thermal insulation needs.

3.6. Acoustic properties

Acoustic properties were analyzed across a frequency range of 300–2000 Hz (Fig. 6) and specified at Table 5. Each sample showed lower values than the control sample (polyurethane) which had the highest value (0.813). It is important to consider that this product had a wavy surface pattern, creating sound traps to enhance its absorption coefficient, and is significantly thick (30 mm). Samples A and B exhibit a higher absorption coefficient (0.644 and 0.640) compared to samples C and D (0.291 and 0.295).

Nonwoven structures A and B showcase increased thickness and air permeability, providing a rationale for their higher absorption

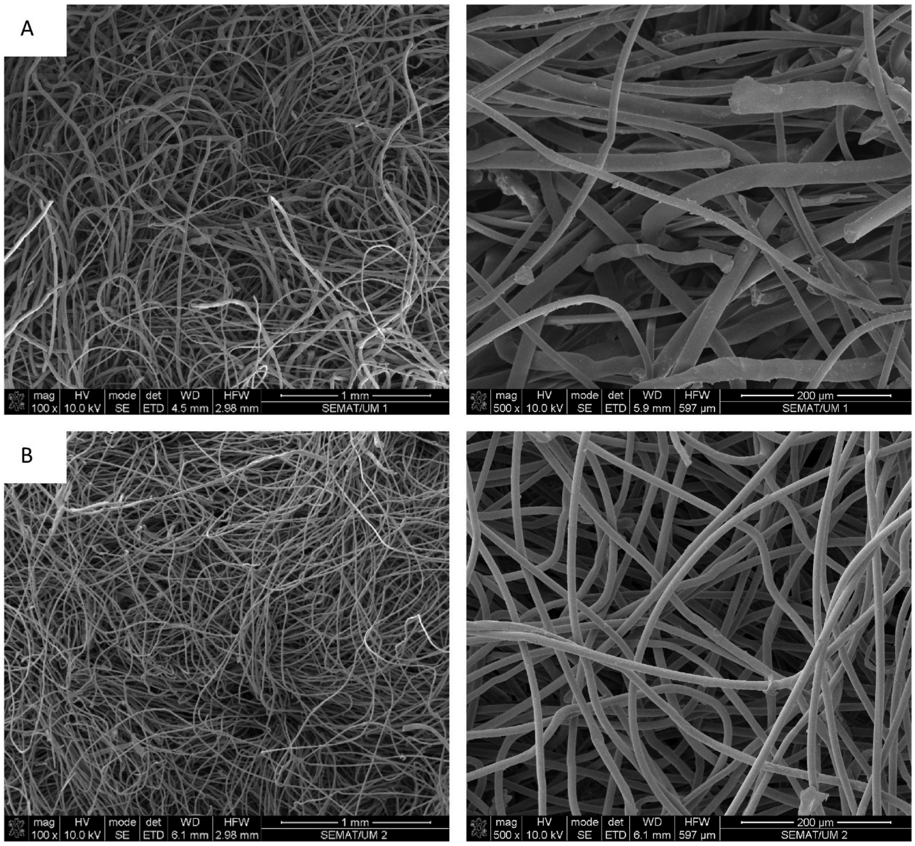

Fig. 4. SEM images of the surface of samples A and B (100× and 500× magnification).

coefficient (Dunne et al., 2017; Sakthivel et al., 2020). Conversely, the compressed nonwoven structures (C and D), owing to their manufacturing process, exhibit higher bulk density, which theoretically should enhance their sound absorption coefficient (Dunne et al., 2017). However, this outcome is accompanied by reduced thickness and lower air permeability, ultimately contributing to a diminished overall performance. Given that the studied samples were not as thick and lacked the surface treatment of the control sample, there is potential to further increase the absorption coefficient, improving its performance. In essence, samples A and B serve as effective acoustic isolation materials suitable for building construction or sound engineering.

In comparison to various nonwoven structures, these samples demonstrated a sound absorption coefficient that, while not as high as several others (polyester + wool (Patnaik et al., 2015), polyester + linen + cotton (Zach et al., 2016), polyester + PP (Trajković et al., 2016)), surpassed that of polyester and cotton (Bogale et al., 2023). When contrasted with other composite materials (Lin et al., 2016; Ricciardi et al., 2014), the studied samples outperformed all but a composite comprising polyester and wool (Rubino et al., 2021). This discrepancy may stem from the fact that most materials in prior studies combined diverse types (cotton, wool, polyester, among others) (Bogale et al., 2023; Patnaik et al., 2015; Ricciardi et al., 2014; Rubino et al., 2021; Zach et al., 2016), whereas this approach involved a single material. Exploring combinations of different materials might enhance results. It is conceivable that incorporating various materials simultaneously could enhance our outcomes. Comparing these results with commonly utilized materials (Ricciardi et al., 2014), neither the studied materials nor those from other studies met the desired value at 500 Hz (0.740–1.000). Notably, these samples, at 5–10 mm thickness, were significantly thinner than the commercially presented samples (40–60 cm) (Ricciardi et al., 2014). Increasing the thickness of the studied samples is expected to raise the sound absorption coefficient.

The compressed nonwoven structures obtained (C and D) yielded values notably below those documented in the literature and commonly employed materials. Consequently, they prove less than ideal for this particular insulation application. This observation aligns with the proposed hypothesis for compressed nonwoven structures, indicating that hot pressing diminishes fiber spacing, elevates composite rigidity, and consequently diminishes its sound absorption coefficient.

4. Conclusion

Nonwoven and compressed nonwoven structures were manufactured from 100% recycled polyester, incorporating 80% footwear waste. Nonwoven structures proved to be adequate substitutes in the evaluated properties, with stronger tensile stress (629–2700 kPa) and a thermal conductivity (0.037–0.060 W/K.m) and sound absorption coefficient (0.291–0.644) that met the employed standards, making them suitable for building construction. These findings demonstrate that waste can be incorporated into recycled materials and used as a replacement for present thermal and acoustic insulation materials in building construction, specifically rock wool. Further tests are required to better understand these materials, including a vibrational study to characterize the viscoelastic properties, impact absorption, flammability evaluation, geometry influence, and a life cycle assessment to determine whether it is a commercially viable option. Recycled materials can and should play an integral role in our society, paving the way for a better tomorrow built on the principles of a circular economy.

Fundings

The authors acknowledge the financial support from integrated project BioShoes4all – Textile Bioeconomy (Investment TC-C12-I01, Sustainable Bioeconomy), promoted by the Recovery and Resilience

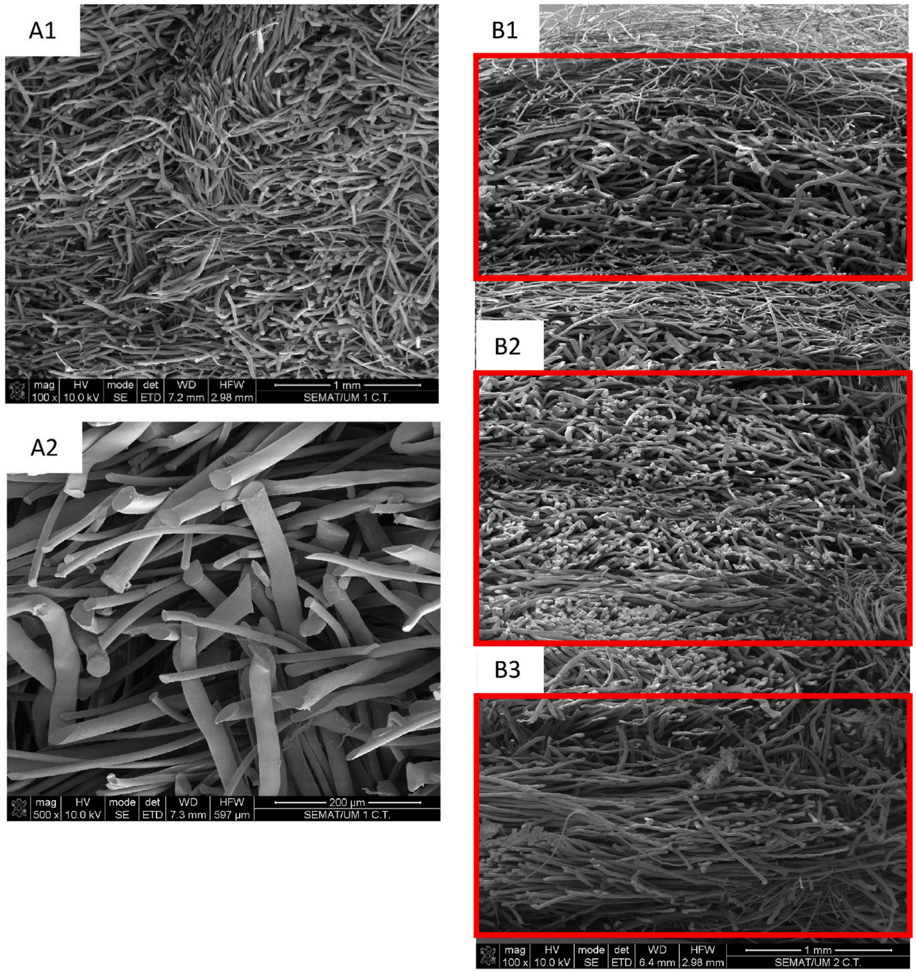

Fig. 5. Cross-section SEM images of samples A and B.

Table 4
Thermal properties of samples and reference values from the literature.

Samples	Thermal conductivity (W/K.m)
A	0.041
B	0.037
C	0.060
D	0.070
Nonwoven: Polyester + Wool (Patnaik et al., 2015)	0.030–0.038
Nonwoven: Polyester + Linen + Cotton (Zach et al., 2016)	0.036–0.050
Nonwoven: Polyester + PP (Trajković et al., 2016)	0.052
	0.060
Nonwoven: Polyester + cotton (Bogale et al., 2023)	0.130–0.170
Composite: Industrial Textile + Paper (Ricciardi et al., 2014)	0.034
Composite: Polyester + Kevlar + Nylon + PP (Lin et al., 2016)	0.026–0.046
Composite: Polyester + Wool (Rubino et al., 2021)	0.044–0.057
Rock wool*	0.040
Cellulose flocks (panels)*	0.039
Kenaf fibers*	0.038
Glass Wool*	0.050
Expanded Polyethylene*	0.040
Mineralized wood fibers Portland Concrete*	0.067

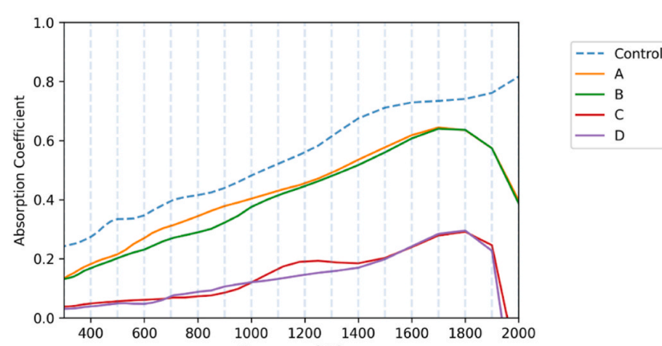

Fig. 6. Absorption coefficient of samples A-D.

Plan (RRP), Next Generation EU, for the period 2023–2026 and European Regional Development Fund through the Operational Competitiveness Program and the National Foundation for Science and Technology of Portugal (FCT) under the projects UID/CTM/00264/2020 of Centre for Textile Science and Technology (2C2T) on its components Base (https://doi.org/10.54499/UIDB/00264/2020) and programmatic (https://doi.org/10.54499/UIDP/00264/2020). This work is also under the national support to R&D unit's grant through the reference project UIDB/04436/2020 and UIDP/04436/2020 and through the project "Mechanobiological device to stimulate cartilage regeneration" with grant reference PTDC/EME-EME/4520/2021. Nuno Fernandes acknowledges the support from FCT for his individual PhD grant with reference 2022.11063. BD. Lívia Tavares Cosentino is also supported by national funds through FCT within the scope of the doctoral Grant PRT/BD/152839/2021, under MIT Portugal Program. Adilson C. Paula Junior is also supported by national funds through FCT

Table 5
Sound absorption coefficient values of obtained samples and values in the literature.

Samples	Sound absorption coefficient (α)	
	500 Hz	1000 Hz–2000 Hz
Control	0.334	0.481–0.816
A	0.215	0.403–0.644
B	0.202	0.375–0.640
C	0.056	0.119–0.291
D	0.049	0.120–0.295
Nonwoven: Polyester + Wool (Patnaik et al., 2015)	–	0.340–0.580
Nonwoven: Polyester + Linen + Cotton (Zach et al., 2016)	0.520	0.650–1.000
Nonwoven: Polyester + PP (Trajković et al., 2016)	0.680	0.700–0.950
Nonwoven: Polyester + Cotton (Bogale et al., 2023)	0.043	0.050–0.290
Composite: Industrial Textile + Paper (Ricciardi et al., 2014)	0.315	0.280–0.450[a]
Composite: Polyester + Kevlar + Nylon + PP (Lin et al., 2016)	0.220	0.000–0.350
Composite: Polyester + Wool (Rubino et al., 2021)	0.670	0.700–1.000
Glass Wool[b]	1.000	–
Cellulose flocks (panels)[b]	1.000	–
Kenaf fibers[b]	0.740	–
Rock wool[b]	0.900	–

[a] Frequency ranges from 1000 to 1600 HZ.
[b] Values taken from (Ricciardi et al., 2014).

within the scope of the doctoral grant SFRH/BD/151345/2021, with funds from the European Social Fund (ESF) and Por Norte Program, under MIT Portugal Program. Diana P. Ferreira is thankful to CEECIND/02803/2017, founded by National Founds through FCT/MCTES, DOI 10.54499/CEECIND/02,803/2017/CP1458/CT0003 (https://doi.org/10.54499/CEECIND/02803/2017/CP1458/CT0003).

Declarations

Conflict of interest

The authors declare no competing interests.

CRediT authorship contribution statement

Diana I. Alves: Writing – original draft, Resources, Methodology, Investigation, Formal analysis, Data curation. **Óscar Carvalho:** Conceptualization, Investigation, Writing – review & editing, Validation, Methodology, Formal analysis, Data curation. **Nuno ATC Fernandes:** Validation, Methodology, Investigation. **Livia Tavares Cosentino:** Methodology, Investigation. **Adilson C. Paula Junior:** Methodology, Investigation. **Raul Fangueiro:** Supervision, Funding acquisition. **Diana P. Ferreira:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Diana Ferreira reports financial support was provided by University of Minho. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.121363.

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