sustainability

IMPACT FACTOR 3.3

CITESCORE 7.7

Review

Textiles Waste as Resources for Relevant Cross-Sectoral Applications, Opening the Cycle to Reach Circular Economy—A Review

Matteo Bertelli, Debora Giorgi, Claudia Morea and Luca Incrocci

MDPI

https://doi.org/10.3390/su18031464

sustainability

Review

Textiles Waste as Resources for Relevant Cross-Sectoral Applications, Opening the Cycle to Reach Circular Economy—A Review

Matteo Bertelli [1,2,*], Debora Giorgi [1,*], Claudia Morea [1] and Luca Incrocci [1]

[1] Department of Architecture, University of Studies of Florence, 50122 Florence, Italy; claudia.morea@unifi.it (C.M.); luca.incrocci@unifi.it (L.I.)
[2] Department of Architecture and Industrial Design, University of Studies of Campania "Luigi Vanvitelli", 81100 Caserta, Italy
* Correspondence: matteo.bertelli@unifi.it (M.B.); debora.giorgi@unifi.it (D.G.)

Abstract

In recent decades, the global fashion and textile market has been facing an unprecedented sector-wide crisis. The growing demand for clothing, combined with continuously decreasing prices and driven by the constant availability of new quantities and styles, has allowed fast fashion and super-fast fashion business models to flood the market with low-quality, short-lived, and high environmental impact products. Starting from 1 January 2025, the separate collection of textile waste came into force in the European Union. However, under current conditions, this regulatory change has generated an imbalance between collection capacity and the availability of effective sorting and recycling channels. Furthermore, due to the low market demand for recycled fibers, warehouses and landfills are increasingly filling with post-consumer textile waste, materials that could potentially serve as secondary raw materials but currently remain unsold. Moreover, the fast fashion business model promotes the use of short fibers and complex fiber blends that are resource-intensive and generate large volumes of low-quality waste. This material profile further limits reuse and recycling options, exacerbating inefficiencies within existing waste management systems. This review aims to identify and discuss available opportunities to address textile waste containing low-quality fibers through the examination of scientific literature, technical publications, and market-ready products that utilize regenerated textile materials. The results highlight open-loop applications and processes, such as those in the automotive, building, and design sectors, thereby opening to new end-of-life scenarios for waste textiles.

Keywords: circular economy; open-loop applications; textile recycling; waste management; industrial symbiosis

Check for updates

Academic Editor: Giovanni De Feo

Received: 27 November 2025
Revised: 17 December 2025
Accepted: 19 January 2026
Published: 02 February 2026

1. Introduction

The textile industry represents the third main cause of land consumption and degradation of global water resources and is estimated to be responsible for approximately 10% of global carbon emissions. According to [1], 124 million tons of textiles were produced in 2023, 15 million more than three years earlier. Of this total, 67% consists of synthetic fibers (polyester, polyamide, etc.), 25% of vegetable fibers (cotton, linen, hemp, etc.), 6% of man-made cellulosic fibers (viscose, acetate, lyocell, etc.), and 1% of animal fibers (wool, silk, etc.).

The European Union was among the first to address the environmental impact of the textile sector by setting the ambitious goal of achieving climate neutrality by 2050. In 2019, it issued the European Green Deal strategy, followed by numerous additional regulations and proposals [2], including the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) regulation [3], the EU Strategy for Sustainable and Circular Textiles [4], the Green Claims Directive [5], the Corporate Sustainability Reporting Directive (CSRD) [6], the Ecodesign for Sustainable Products Regulation (ESPR) [7], the Packaging and Packaging Waste Regulation (PPWR) [8], the EU Waste Framework Directive and Extended Producer Responsibility for Textiles (EPR) [9], and the Right to Repair initiative [10].

Statistics reported in [11] show that, despite the challenges faced and the global and European objectives set, the fashion market continues to grow, with fiber production estimated to reach 145 million tons by 2030. Each year, a European citizen purchases approximately 26 kg of textile products, while in the same period about 11 kg per capita, over 40% of purchases, is discarded. However, only 1% of clothing disposed of is recycled into new garments (i.e., closed-loop or fiber-to-fiber recycling), and the share of recycled fibers on the market amounts to 12% for polyester, 6% for wool, and 3% for elastane, decreasing further to 0.3% for polypropylene [1].

In Europe, the quantity of textile waste exceeds 12 million tons, and globally this number continues to rise, reaching approximately 92 million tons. Of this total, only 25% is correctly collected, separated, and reused or recycled, while the remaining 75% is sent to incineration or landfilling [12].

In this context, and given the continuous growth of the sector, the European Union is approving projects and funding for the construction of hubs dedicated to textile collection and sorting. These facilities are designed as large-scale warehouses capable of storing thousands of tons of textile waste, where end-of-life (EoL) processes for textiles can be carried out. Moreover, significant investments have been made in (semi-)automatic sorting technologies, increasing the efficiency of the selection phase. However, numerous testimonies from recycling hubs and trade associations involved in textile collection and sorting indicate that textile products that do not fall within the "second-hand" category and whose fibers are not suitable for fiber-to-fiber recycling struggle to find market demand.

Siptex, built in Malmö (Sweden), was the world's first textile recycling hub featuring an industrial-scale automatic sorting plant for post-consumer waste. The facility uses near-infrared (NIR) and visual spectroscopy (VIS) technologies to sort textile waste based on market requirements, particularly fiber, composition, and colors. In its reporting, Siptex highlighted several significant findings, including that the presence of chemical substances in the selected materials does not pose a major issue with respect to REACH regulations, as in most cases these substances appear to have evaporated or been washed out during the use phase of textile products. Nevertheless, despite these promising premises, the project confirms that its main challenge remains the identification of viable markets for sorted textile waste [13], particularly for fractions containing low-quality fibers and complex blends composed of three or more fibers.

Within this complex framework, the present literature review seeks to identify market opportunities by offering a realistic overview of the current situation and the potential EoL scenarios for textile waste in cross-sectoral applications. As noted by [14] in a 2018 study, knowledge of market demand significantly influences the proportion of textile waste that can be effectively selected, even when analyzing identical material samples.

2. Materials and Methods

This study presents a literature review on the valorization of textile waste for open-loop recycling processes. The review was conducted through the examination of scientific articles, technical publications, and products already available on the market that use textile materials derived mainly from pre-consumer and post-consumer waste. The research methodology was structured into four main steps:

1. Definition of the research question—The review addresses how the growing demand for the management of low-quality textile materials, primarily originating from post-consumer waste, can be met through industrial symbiosis and the use of textile waste in open-loop recycling processes. Attention is given to cross-sectoral applications, including the automotive, biofuels, building and construction, footwear, furniture and interior design, horticultural, packaging, and medical and care sectors.
2. Identification of databases and definition of inclusion or exclusion criteria for articles—The main databases used for literature retrieval were Scopus, Google Scholar, and Web of Science. The search was conducted between 1 April 2024 and 1 November 2025, and the selected publications fall within the time range 2000–2025.
3. Articles were identified using keyword-based search strings, including "Recycling of textile waste", "Post-consumer textiles recycling", "Pre-consumer textiles recycling", "Cross-sectoral application of textiles", "Cross-sector recycling of textiles", "Enhancement of textile waste", "Textile waste management", "Textile waste circularity", "Recycling of textile fibers", "End of textile waste", "End-of-life textile product", "EU textile waste directive", and "Closed-loop recycling textiles".
4. In parallel, an online market analysis of products already commercialized was conducted to better define the scope of application and contextualize the reviewed studies. Once the main cross-sectoral applications of pre- and post-consumer textile waste were identified, additional targeted keywords were used, such as "Waste textile fibers in automotive sector", "Waste textile fibers in the building sector", "Textile waste for non-woven applications", "Textile fibers for composites", "Textile waste in construction materials", "Textile fibers for automotive applications", "Textile waste in insulation products", "Textile fibers for packaging", "Textile waste in additive manufacturing", "Textile waste in medical and care sector", "Textile waste in biofuels production", "Textile waste in footwear sector", "Textile waste in furniture and interior design", and "Textile waste in horticultural applications".
5. Screening and recording of results/data extrapolated from sources—The initial search yielded several hundred articles. To manage the scope of the review, an initial screening was performed based on titles, abstracts, and keywords. This process resulted in the selection of 48 core articles, distributed across cross-sectoral applications as follows: automotive (5), building and construction (33), and other cross-sectoral applications (10). In addition, 34 supplementary articles and web sources were reviewed to provide a broader contextual understanding of the textile and fashion sector and textile waste management.
6. Summary of the results—The findings were synthesized and organized using online tools (Miro and Airtable). Key material properties, performance indicators, and application outcomes were summarized and systematically reported in tabular and visual form.

3. Results

3.1. Cross-Sectoral Applications of Textiles Waste

Textile waste (TW) represents a significant potential source of secondary raw materials, and its valorization can substantially reduce landfill disposal while supporting circular economy principles [15,16]. Approximately 90% of global textile waste is technically recyclable [17]; however, recycling processes suitable for textile regeneration are highly variable and are constrained by several factors that limit closed-loop recycling [15]:

https://doi.org/10.3390/su18031464

- The maturity of existing technologies on the market on an industrial scale.
- The cost of the technologies used and the resulting price increase for the final products on the market.
- The complexity of textile fibers and therefore of fabrics.
- The complex logistics that concern both the collection of waste and its quantity, which is not always adequate or sufficient to be sent for recycling.
- The environmental impact of technologies, particularly chemical technologies.

Eco-design strategies and the use of higher-quality fibers or blends limited to a maximum of two fiber types can partially extend product lifespans and mitigate recycling challenges at the end-of-life stage. Nevertheless, fiber lifespans are finite, especially in mechanical closed-loop recycling, where fibers degrade with each cycle [15]. Plastic fibers typically withstand a maximum of 7–9 recycling cycles, cellulosic fibers 4–6 cycles [18], and wool fibers similarly 4–6 cycles before becoming unsuitable for further fiber-to-fiber recycling [19]. Consequently, identifying applications for the growing volume of low-quality and deteriorated fibers is both essential and strategic.

3.2. Building and Construction Sector

The construction sector emerges as one of the primary application areas for textile waste, with extensive literature addressing this topic, including comprehensive reviews such as ref. [20]. Construction applications enable the use of large quantities of textile materials, reinforcing their role in energy savings and environmental impact reduction [16].

3.2.1. Thermal and Acoustic Insulations

Passive building design is a key response to the sector's energy demand, as effective thermal insulation can reduce energy consumption for thermoregulation by up to 65% [21]. Textile waste is widely applied in thermal insulation, often in the form of non-woven fabrics, addressing both the disposal of large textile volumes and the reduction of material degradation in landfills [22].

Wool, polyester, and polyurethane are among the most commonly used fibers due to their low thermal conductivity and sound absorption properties [16]. A 2015 study [23] combined waste wool and recycled polyester in a 50:50 two-layer panel, achieving high thermal insulation and acoustic performance, with over 70% sound absorption in the 50–5700 Hz frequency range, adequate moisture resistance, and 65–70% biodegradation within 50 days.

In general, non-woven fabric panels designed for thermal insulation also exhibit acoustic properties. For example, ref. [24] investigates a jute–polypropylene (1:1) composition produced by needle punching to evaluate both thermal and acoustic performance.

Not only fibers but also fabric scraps can be used as secondary raw materials, as demonstrated in [25]. The non-woven panel analyzed in this study is produced from pre-industrial nylon/spandex and polyurethane waste, a blend that is widespread on the market yet particularly challenging to recycle. The sample, manufactured through compression molding, exploits the intrinsic properties of the constituent fibers, such as the excellent thermal insulation capacity of polyurethane and the binding function of nylon during the melting process, resulting in a rigid composite material.

Products intended for the construction sector must meet stringent standards, including resistance to humidity and decomposition, microbial attack, dimensional stability, and hygrothermal performance. In this context, ref. [26] uses jute, flax, and hemp to develop new insulating materials from renewable resources, achieving physical and mechanical properties comparable to conventional insulation products. The performance of these non-woven panels is fully comparable to that of traditional insulation solutions. Conventional materials, in fact, present several drawbacks, such as the irritating nature of glass and rock wool, the emission of gases from polystyrene when exposed to heat, the limited recyclability of polyurethane, and, more importantly, their dependence on petroleum-based raw materials. Against this background, ref. [27] evaluates four needle-punched non-woven samples made of wool and acrylic, reporting excellent thermal performance, with the lowest measured thermal conductivity reaching 0.03476 W/mK.

To develop products that are attractive to the market, not only the choice of raw materials but also the production process plays a crucial role. Accordingly, ref. [28] develops an innovative, low-impact manufacturing process for semi-rigid wool and hemp panels with both thermal and acoustic performance, characterized by low environmental impact and reduced production costs.

In the field of sound insulation, non-woven fabrics are particularly suitable due to the porosity of their structure, which is a fundamental requirement for effective sound absorption. Porosity enables sound waves to penetrate the material matrix and be dissipated through air molecule vibration and the conversion of kinetic energy into thermal energy [29]. Panels with lower density, typically produced through random-laid processes, show greater sound reduction compared to cross-laid or parallel-laid structures [24].

Moreover, several studies report that the noise absorption coefficients of non-woven panels are comparable to those of rock wool or glass fiber insulation in the high-frequency range [30]. The combination of waste materials from different supply chains can also lead to innovative solutions, as demonstrated by [31], which develops a panel composed of polyethylene fibers, waste paper, and wool.

Rigid polyurethane foam is currently among the most effective materials for thermal and acoustic insulation. In [32], the incorporation of textile waste in varying proportions into polyurethane-based panels is investigated to enhance acoustic performance. The best results are obtained with a composition containing 40% textile waste and 60% rigid polyurethane foam, achieving a maximum Noise Reduction Coefficient (NRC) of 0.593, which is twice that of panels made entirely of rigid polyurethane foam.

Finally, ref. [33] presents the development of medium- and high-density insulating mats suitable for vertical constructions and floating floor systems. These insulation materials are produced either from purely synthetic polyester (PES) fibers or from blends of polyester and cotton fibers thermally bonded using bicomponent fibers.

3.2.2. Reinforcement for Composites

The second most common category of products in the construction sector relevant to this review is composite materials, defined as products consisting of a matrix in which a reinforcement with high mechanical properties is embedded.

According to [34], not only synthetic fibers but also natural fibers show significant potential for this type of application due to their low weight, ability to be shaped into complex geometries, and favorable mechanical properties in terms of elongation, tensile strength, and fracture behavior. In this study, ref. [34] performs an application analysis of natural fibers such as flax, hemp, kenaf, sisal, and jute.

Similarly, ref. [18] conducted a study in 2019 aimed at recovering various end-of-life fabrics for use as secondary raw materials in the development of textile-reinforced composite materials (TFRC). The samples, composed mainly of polymeric fibers, cotton, wool, acrylic, polyester, polypropylene, nylon, and elastane, were not used as individual fibers but rather as fabric pieces approximately 2×2 cm in size. The results demonstrated high compatibility among fibers in composite blends, identifying textiles as a viable, non-toxic, and low-carbon alternative for this class of materials.

The use of fibers as reinforcement in cement or mortar is not a recent practice, given the intrinsic characteristics of these materials, composed of binders (cement and/or lime), fine aggregates (sand), and water, which make them well suited for the incorporation of additives to enhance final product performance [35]. In this context, ref. [36] investigates the use of 100% cotton fibers derived from blue jeans, ref. [37] conducts tests with fibers composed of 30% wool and 70% acrylic, and ref. [38] examines polymer fibers.

The latter study focuses on polymer concrete (PC), which is already employed in prefabricated components, lightweight and low-cost constructions, bridge panels, buildings, and transport-related elements. In this case, polymer fibers are blended with thermosetting resins and foundry sand. Although the final mechanical performance does not fully meet initial expectations, the resulting material exhibits properties comparable to unreinforced Portland cement concrete, proving suitable for concrete repair applications and showing reduced signs of fragility due to the presence of textile fibers in the mixture.

The complexity and variability of fibers suitable for reinforcement applications are considerable, and the resulting performance does not always meet required standards. This limitation is confirmed by the study presented in [35], in which a mortar mixture containing 3% textile waste fibers of 3 cm length shows good adhesion strength but suboptimal tensile strength, failing to meet regulatory requirements.

Instead, ref. [39] demonstrates that the compressive strength of concrete reinforced with fibrillated fibers increases by 25% compared to standard concrete compositions. The inclusion of fiber provides enhanced crack resistance under bending, improved resistance to dynamic loads, greater fatigue resistance, and improved thermal resistance to sudden temperature changes, albeit with reduced grindability compared to conventional concrete.

Despite some performance limitations, the environmental benefits associated with textile waste recycling remain significant. In this regard, ref. [40] explores the use of waste materials such as fishing nets, which do not require energy-intensive processes like polymerization or extrusion for regeneration, but instead involve simple steps such as collection, washing, and cutting. The nylon fibers tested in this study lead to notable improvements in tensile strength, up to +35%, and toughness, up to 13 times greater than conventional materials.

Furthermore, ref. [41] investigates the use of pre-consumer textile waste composed of 70% wool, 25% viscose, and 5% elastane, incorporated at varying proportions into lightweight, non-structural concrete blocks. The inclusion of fibers serves a dual function: on the one hand, it enhances thermal insulation performance, with measured thermal conductivity values of 0.294 W/m °C, 0.164 W/m °C, and 0.2149 W/m °C for the three samples, respectively; on the other hand, it highlights the need for further research in this field. Indeed, ref. [41] emphasizes that additional studies are required to fully explore the potential of textile waste applications in the construction sector, opening new research directions and methodological approaches.

Finally, ref. [42] reports experimental results on a brick composed of textile waste, limestone dust waste, cement as a binder, and water, achieving a weight reduction of approximately 60% compared to conventional bricks.

3.2.3. Geotextiles & Soil Composites Reinforcement

Starting with the use of fibers in composite materials, such as cement and mortar, this practice has also spread to asphalt production and reinforcement of soil composites.

The fibers employed include both synthetic fibers, such as glass, carbon, and polymers, and natural fibers, such as hemp, coconut fiber, jute, sisal, and linen. In this context, ref. [43] investigates the addition of aramid–polyalphaolefin polymeric fibers in Asphalt

https://doi.org/10.3390/su18031464

Fiber Reinforced Concrete (AFRC) to improve performance characteristics, particularly low-temperature crack resistance.

Similarly, ref. [44] analyzes the effects of polypropylene, polyester, cellulose, and nylon fibers on cement–asphalt mixtures, focusing on improvements in viscoelastic behavior as well as modifications to dynamic modulus, moisture susceptibility, creep compliance, rutting resistance, freeze–thaw resistance, and crack reduction.

The study presented in [45] examines the effects of polypropylene fibers on the mechanical behavior of both uncemented and cemented clay soils. The addition of fiber reinforcement results in a significant increase in strength and a reduction in soil stiffness. More importantly, fiber-reinforced soils exhibit greater toughness and ductility, along with reduced post-peak strength loss, compared to untreated soils. Consistent with these findings, ref. [46] reports similar results, emphasizing the advantages of randomly distributed fibers as reinforcement in enhancing the ductility of the final material.

Rapid urbanization and the resulting reduction of arable land, particularly in urban areas, have often led to a decline in green spaces and, consequently, biodiversity. In the field of geotextiles, ref. [47] proposes combining mechanical textile recycling techniques, such as carding and needling, with an ultraviolet-aging finishing treatment. The resulting geotextile is low cost, environmentally friendly, and characterized by good permeability, mechanical resistance, and anti-aging properties, while being capable of replacing riparian soil to support normal plant growth. The material used consists of textile waste (TW) composed of 78% polyester, 20% cotton, and 2% other fibers.

3.3. Automotive and Transport Sector

The thermal, acoustic, and thermoforming properties of waste fibers and nonwoven fabrics are widely exploited in the automotive sector and, more broadly, in the transport industry. As early as 2004, ref. [48] reported that more than 40 components in an automobile were made of nonwoven fabrics, with this number continuing to increase. These materials are not used for structural purposes but instead find extensive application in comfort-related components, in line with the intrinsic properties of fibrous materials.

Study [49] employs needle-punching and molding technologies to produce a rear trunk component made of recycled polyester (rPET) coated with a polyethylene/vinyl-based recycled polymer film. Rear trunk components require both sound absorption and adequate resistance to tensile and abrasive stresses. When compared with existing market products, the solution composed of PET combined with a film (50% PE and 50% VBR) demonstrates excellent performance.

In the automotive sector, carpets also require effective sound-absorbing properties. Studies [50,51] present two investigations addressing this requirement. The first study, conducted in 2014, aims to reduce sound transmission through nonwoven fabrics by evaluating acoustic performance across a frequency range of 126–6300 Hz, demonstrating that the inclusion of a nonwoven layer within the product stratigraphy significantly enhances acoustic performance. The second study, published in 2020, demonstrates the feasibility of producing a carpet that meets requirements for environmental sustainability, low cost, and high abrasion resistance. Despite the documented quality degradation of polyester during recycling, the study confirms the feasibility of designing a product that satisfies the stringent performance standards of the sector, including abrasion resistance, defined as the number of cycles required to cause disintegration or a specified weight loss. The carpet is manufactured using needle punching and consists of 80–85% recycled polyester (combining 6 and 11 denier fibers) and 15–20% bicomponent fibers.

The pursuit of higher performance in automotive applications, particularly for lightweight components, has led to increased research interest in bio-prepregs. These composite materials are produced by impregnating natural or recycled fibers with bio-based resins, resulting in rigid panels with customizable textures. Study [52] provides an overview of bio-prepregs in the automotive sector, focusing on the use of natural ligno-cellulosic fibers as reinforcement and polymers either directly produced by organisms or synthesized from bio-based monomers as the matrix material.

3.4. Other Cross-Sectoral Applications

Not only the building and automotive sectors offer solutions for the use of regenerated fibers. Study [53] examines approaches for reusing waste cotton/polyester blends as reinforcement in composite materials.

Study [54] investigates a sustainable pathway for upcycling textile waste by integrating medium- to long-length cotton and flax fibers, sourced from end-of-life fabrics, into a bio-based thermoplastic matrix, namely polylactic acid (PLA). Similarly, ref. [55] uses cotton textile waste mixed with a bio-based polyethylene terephthalate (bio-PET) matrix to explore its added value as reinforcement in composite materials.

The results obtained from these studies pave the way for the experimentation of materials with suitable properties for application across various sectors. Market research has shown that secondary raw material fibers are already employed in fields such as accessories, gadgets, packaging, furniture, interior products [56], and household appliances. Study [57] provides an overview of fiber and fabric recycling, focusing on carpets, which represent a significant share of textile waste.

Study [58] focuses on the production of a nonwoven fabric based on jute and polyester, subsequently treated with an antibacterial coating applied by spraying a solution of silver nitrate, ethanol, and ammonia. The developed sample exhibits an elongation of 2.3% and a breaking force of 170.8 N, while also demonstrating water-repellent behavior and a low thermal conductivity of 0.0839 W/mK. Owing to its antibacterial properties, tested against Staphylococcus aureus and Escherichia coli, the resulting product is suitable for both food and medical packaging applications.

In 2020, ref. [59] published a study on the production of nonwovens laminated with mechanically recycled textile fibers for medical applications. The compositions investigated included 100% recycled cotton; 50% polycotton + 20% pulp + 30% bicomponent fibers; and 25% unrefined cotton + 45% refined cotton + 30% bicomponent fibers. The study conducted extensive analyses and testing, demonstrating the feasibility of producing laminated rolls suitable for hospital sheets and absorbent products.

Most studies focus on the mechanical rather than chemical recycling of textile waste. In contrast, ref. [60] proposes biological treatments, highlighting their reliability and environmental compatibility in exploiting the intrinsic value of textile waste. In this study, organic matter is converted into biofertilizers and bioenergy.

More recently, the field of additive manufacturing (3D printing) has also attracted increasing interest. These processes can incorporate recycled textile fibers, often blended with bio-resins or polymer matrices, to produce lightweight, customized interior components, decorative objects, and functional prototypes. Study [61] examines the growing integration of natural fibers into 3D printing processes to enhance environmental sustainability.

4. Discussion

Many technologies are employed to manage textile waste. On the one hand, chemical recycling is primarily applied to closed-loop recycling pathways; however, further development is required, particularly regarding environmental and economic impacts. Biological recycling is still technologically emerging, but its potential is considerable: it can selectively process fiber blends, avoids the use of harsh chemicals, and reduces environmental

https://doi.org/10.3390/su18031464

footprint, provided that the textiles are clean and free from finishes that inhibit biological activity [60].

At present, mechanical recycling appears to be one of the most mature and widely applicable technologies at the industrial scale for open-loop processes. Among the products obtained through mechanical recycling, nonwoven fabrics represent a significant area of application for textile waste, including low-quality fibers. Owing to their versatility, these products are becoming increasingly attractive to designers and planners. Both the market and the scientific literature report numerous companies and researchers investigating the potential for fiber regeneration in nonwoven fabric panels.

This type of product finds applications across multiple sectors due to favorable characteristics such as low weight, low cost, and good thermal and acoustic performance. For these reasons, application areas are highly diverse, ranging from the automotive to the construction sector. The fibers used in nonwoven fabrics may be virgin, secondary raw materials, or a combination of both.

The conversion of waste textile materials into nonwoven fabrics does not follow a rigid, standardized process. Rather, as the characteristics of textile waste vary (pre-consumer or post-consumer origin; synthetic, vegetal, or animal fibers), the transformation processes also differ accordingly. Recycling typically begins with material selection, usually still in fabric form, based on fiber type, color, and quality. The textile is then cut into small pieces and opened back into fibers, which are generally too short to be respun. In the case of nonwoven fabrics, the main processing steps include the following [16]:

- Web formation: the process in which fibers, arranged randomly, are formed into a sheet structure using various technologies, such as dry-laid webs (e.g., air-laid), wet-laid webs, foam-laid webs, spun-melt processes (e.g., spunbonding and meltblowing), and film casting.
- Web bonding: the step that stabilizes and strengthens the sheet structure obtained in the previous phase, which can be achieved through chemical (e.g., chemical binders), thermal (also using pressure), or mechanical processes (e.g., needle punching).
- Finishing: the final set of transformations that impart the desired properties to the material before it is ready for market introduction.

Nonwovens represent a substantial share of the fiber regeneration market, but they do not encompass all possible applications. The literature also provides valuable insights into the production of composite materials and additively manufactured products. However, despite the increasing use of fibers in these applications, high performance requirements often favor the use of virgin fibers over recycled ones, due to their more consistent and predictable properties.

5. Conclusions

After reuse and repair strategies, recycling represents the third most relevant end-of-life solution for managing both pre-consumer and post-consumer textile waste. Its strategic importance is expected to increase further, considering the large volumes of low-value textile products introduced to the market over recent decades and the consequent pressure this will place on end-of-life management systems. In this context, open-loop recycling currently plays a central role, as it allows the valorization of medium- to low-quality materials; however, this often results in downcycled products with limited functional performance and reduced economic value.

One of the main systemic barriers identified is the difficulty in meeting defined technical standards and performance requirements when using secondary raw materials derived from highly heterogeneous post-consumer textile waste. This variability, caused from fiber composition, finishing treatments, and product design, directly affects process stabil-

https://doi.org/10.3390/su18031464

ity, product quality, and market acceptance. Additionally, several recycling technologies require complex and cost-intensive treatments, which currently limit their economic competitiveness and scalability under existing market conditions.

Nevertheless, recent advances in mechanical, chemical, and biological recycling technologies indicate a significant shift in this landscape. These developments demonstrate an increasing capacity to transform textile waste into secondary raw materials suitable for higher-value applications, potentially reducing the traditional gap between virgin and recycled fibers. This evolution suggests that closed-loop recycling should no longer be considered solely a downcycling solution but a dynamic and technology-dependent pathway whose performance is strongly influenced by input material quality and system design.

The literature analysis highlights a strong concentration of research and industrial implementation in acoustic and thermal applications, particularly within the automotive and construction sectors, where products are already commercially available. In contrast, fewer studies address other sectors, such as packaging or medical applications, reflecting both stricter regulatory constraints and a lower level of technological maturity. Nonetheless, selected studies demonstrate promising solutions, such as [60], indicating that these underexplored sectors may represent relevant future outlets for recycled textile fibers.

Overall, the articles analyzed and summarized in Table A1 underline the growing potential of textile waste as a secondary raw material. This review supports the industrial adoption of recycled fibers not only in well-established application domains but also in alternative and emerging pathways, emphasizing the need for improved material characterization, targeted recycling strategies, and closer alignment between textile design, sorting technologies, and end-use requirements.

Author Contributions: Conceptualization, M.B.; methodology, M.B.; validation, D.G., L.I., and C.M.; formal analysis, M.B., L.I., and C.M.; investigation, M.B.; data curation, M.B.; writing—original draft preparation, M.B.; writing—review and editing, M.B.; supervision, D.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Ministry of University and Research (MUR), Italy, through the NextGenerationEU and National Recovery and Resilience Plan (PNRR), Extended Partnership "Made in Italy Circolare e Sostenibile"; Project N.: PE_00000004. The Article Processing Charge (APC) was funded by Research funds of the national doctoral "Design for Made in Italy: Identity, Innovation and Sustainability" and by University of Florence.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

Eol	End-of-life
TW	Textiles waste
PCW	Post-consumer waste
PreCW	Pre-consumer waste
PIW	Pre-industrial waste
Rm	Raw material
Rt	Recycled textiles

Appendix A.

Table A1. Summary of open-loop recycling application for textile waste.

Application/Composition	Study's Details	Input	Recycling Technologies	Reference
Automotive				
Rear trunk				
50% Polyester + 50% Polyethylene		Rt	Needle punching	[49]
Carpet				
22% (75%) Cotton + (25%) Phenolic resin + 3.5% SBR Latex + 3.5% PE powder + 71% EVA rubber or EPDM		Rm	Needle punching	[50]
45% recycled Polyester (6 denier) + 40% recycled Polyester (11 denier) + 15% Bico PET		PCW	Needle punching and molding	[51]
Building				
Thermal panels				
50% Wool scrap + 50% Polyester		PCW	Needle punching	[23]
50% Jute + 50% Polypropylene			Needle punching	[24]
60% Nylon6 (75–95%)/Spandex (25–5%) + 40% Polyurethane	*Thermal conductivity* = 0.0953 W/mK	PreCW	Compression molding	[25]
Jute, Flax or Hemp				[26]
50% Wool + 50% Hemp	*Thermal transmittance* = 0.41 W/m^{2}K *Sound absorption frequency* = 100–5000 Hz	PreCW and PCW		[28]
100% Acrylic or 100% Wool	*Sample thickness* = 10 mm *Thermal conductivity* (W/mK) = As > 0.0431, Ak > 0.0429, Wc > 0.03827, Wr > 0.037/40	PCW	Needle punching	[29]
Hemp, Straw, Cellulose fibres		PreCW and PCW		[62]
Acoustic panel				
50% Waste Paper + 50% Wool fleece	*Sample thickness* = 50 mm	PreCW and PCW		[31]
40% Textile scrap (15% Polyamide, 40% Polyacrylic, 45% modal) + 60% Rigid polyurethane foam	*Sample thickness* = 40 mm *Frequency range* = 250/900 Hz, 1400/3100 Hz *For indoor and outdoor*	PreCW (knitted production clothing)		[32]
80% Polyester fibers + 20% binder or 80% Polyester/Cotton + 20% binder	*Fiber thickness* = 10–15 µm *Fiber length* = 15–25 mm *Thermal conductivity* = 0.0396 W/mK	PreCW and PCW	Thermal bounding	[33]
Reinforcement for composites				
Hute, Flax, or Hemp		Rt	Loose fibers in the mixture	[34]
60% Mixed fleece (Wool) + 40% Polypropylene		PCW	Loose fibers in the mixture	[18]
100% Cotton (Blue Jeans)		PCW	(*Shedding processes* = square pieces 1 × 1 cm, *knife mill* = 4 cycle of 15 s each)	[36]
Polymer Concrete (PC)				
Cotton, Polyester, Silk, Rayon (1–2% by weight of composite)	*Type of waste* = lingerie *Waste length* = 2–6 cm *Other materials in the composite* = Epoxy Resin (RR515 by SILAEX) + quartz sand	PreCW	Loose fibers in the mixture	[38]
Coating and mortars				
Unknown	*Fiber length* = 30 mm	PCW	Loose fibers in the mixture	[35]
70% Wool + 30% Acrylic	*Yarn diameter* = 1 mm *Yarn length* = 2–4 cm	PreCW	Loose fibers in the mixture	[37]
0.75% (by weight of composite) Polypropylene	*Fiber length* = 10 mm *Fibrillated fibers*		Loose fibers in the mixture	[39]
Nylon6 (1–1.5% by weight of composite)	*Type of waste* = fishing nets *Fiber diameter* = 0.33 mm *Fiber length* = 12.7/25.4/38.2 mm *Tensile strength* = +35%	PCW	Loose fibers in the mixture	[40]
Lightweight blocks (Non-structural elements)				
70% Wool + 25% Viscose + 5% Elastane	*Waste dimension* = max 3 cm	PreCW	Loose fibers in the mixture	[41]
10–40% Cotton	*Fiber length* = 100 µm	PIW		[42]
Geotextiles and soil composites reinforcement				
Asphalt concrete				
0.05% (by weight of composite) Aramid-polyalphaolefin	*Fiber length* = 19 mm	Rm	Loose fibers in the mixture	[43]
Synthetic fibers: Glass, Carbon, Polymer & natural: Hemp, Coir, Jute, Sisal, Flax				[63]
Soil composite				
Polypropylene fiber (PP), 0.05/0.15/0.25% (by weight of composite) + Portland cement	*Fiber length* = 12 mm	Rm	Loose fibers in the mixture	[45]
Polypropylene fibers + Sand	*Fiber length* = 20 mm *Fiber diameter* = 0.05 mm	Rm	Loose fibers in the mixture	[46]
Geotextiles (Support for plants roots)				

Table A1. *Cont.*

Application/Composition	Study's Details	Input	Recycling Technologies	Reference
78% Polyester, 20% Cotton, 2% Other		PreCW and PCW	Carding, needle punching (*needle depth* = 12 mm, *needling frequency* = 700 times/min), UV-aging (*light intensity* = 1 W/mq *box temperature* = 60 °C *UV wave length* = 340 nm)	[47]
Furniture and Interiors				
Fiber composites				
Polypropylene (MFI 3.5 g/10 min) + denim Cotton	*Defect* = color nonstandard	Rm, PreCW, and PCW		[64]
50% Cotton + 50% Polyester	*Matrix* = thermoplastic copolyester/polyester bi-component fiber *Tensile strength* = 88 MPa		Carding (40 Hz, 7.5 m/min) + needle-punching (200 cp/min, feed rate 1.5 m/mm) + laminating (150° × 2 h) + heat compression molding	[53]
Carpet				
100% Polypropylene				[56]
Packaging				
Food and Medical				
70% Jute + 30% Polyester	*Breaking force* = 170.8 N *Thermal conductivity* = 0.0839 W/mK *Antibacterial resistances* = *Staphylococcus aureus, Escherichia coli*	PreCW	Carding	[58]
Medical and care				
Laminated nonwoven products				
100% recycled Cotton or 50% Polycotton + 20% Pulp + 30% Bi-component or 25% unrefined Cotton + 45% refined Cotton + 30% Bi-component		PreCW and PCW	Carding and laminating	[59]
Horticultural				
Biofertilizer and Energy				
Wool, Cotton, Synthetic cellulosic materials (Jeans)		Rt	Composting	[60]
Wool, Cotton, Cellulosic, Jeans		Rt	Bioaugmentation	[62]

The value reported in the table refers to the best solution analyzed in the same article.

References

1. Materials Market Report—2024—Textile Exchange. Available online: https://textileexchange.org/knowledge-center/reports/materials-market-report-2024/ (accessed on 5 November 2024).
2. Guida al Panorama Legislativo Tessile dell'UE per il 2024—Recovo. Available online: https://recovo.co/it/blog/article/legislazione-europea-sui-tessili (accessed on 10 October 2025).
3. Registration, Evaluation, Authorization and Restriction of Chemicals. Available online: https://environment.ec.europa.eu/topics/chemicals/reach-regulation_en (accessed on 10 May 2024).
4. EU Strategy for Sustainable and Circular Textiles. Available online: https://environment.ec.europa.eu/strategy/textiles-strategy_en#implementation (accessed on 8 April 2024).
5. Green Claims Directive. Available online: https://environment.ec.europa.eu/topics/circular-economy/green-claims_en (accessed on 22 June 2024).
6. Corporate Sustainability Reporting Directive. Available online: https://finance.ec.europa.eu/capital-markets-union-and-financial-markets/company-reporting-and-auditing/company-reporting/corporate-sustainability-reporting_en (accessed on 10 October 2025).
7. Ecodesign for Sustainable Product Regulation. Available online: https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/ecodesign-sustainable-products-regulation_en (accessed on 20 July 2024).
8. Packaging and Packaging Waste Regulation. Available online: https://environment.ec.europa.eu/topics/waste-and-recycling/packaging-waste_en (accessed on 2 March 2025).
9. EU Waste Framework and Extended Producer Responsibility for Textiles. Available online: https://environment.ec.europa.eu/topics/waste-and-recycling/waste-framework-directive_en (accessed on 10 March 2025).
10. Right to Repair. Available online: https://www.europarl.europa.eu/news/en/press-room/20240419IPR20590/right-to-repair-making-repair-easier-and-more-appealing-to-consumers (accessed on 17 May 2025).
11. European Environmental Agency. Available online: https://www.eea.europa.eu/en (accessed on 4 September 2025).

12. A New Textiles Economy—Redesigning Fashions Future—Ellen MacArthur Foundation Reports. Available online: https://www.ellenmacarthurfoundation.org/topics/measurement/overview (accessed on 10 September 2025).
13. *Swedish Innovation Platform for Textile Sorting—A Summary Report of the Final Stage of the Project; Siptex Summary; Report*; IVL Swedish Environmental Research Institute Ltd.: Stockholm, Sweden, 2022.
14. Nørup, N.; Pihl, K.; Damgaard, A.; Scheutz, C. Development and testing of a sorting and quality assessment method for textile waste. *Waste Manag.* **2018**, *79*, 8–21. [CrossRef] [PubMed]
15. Schmutz, M.; Som, C. Identifying the potential for circularity of industrial textile waste generated within Swiss companies. *Resour. Conserv. Recycl.* **2022**, *182*, 106132. [CrossRef]
16. Islam, S.; Bhat, G. Environmentally-friendly thermal and acoustic insulation materials from recycled textiles. *J. Environ. Manag.* **2019**, *251*, 109536. [CrossRef] [PubMed]
17. Arun, C.M.; Panneerselvan, L.; Nachimuthu, G.; Conaty, M.; Palanisami, T. Eco-innovative approaches for recycling non-polyester/cotton blended textiles. *Waste Manag. Bull.* **2025**, *3*, 255–270. [CrossRef]
18. Echeverria, C.A.; Handoko, W.; Pahlevani, F.; Sahajwalla, V. Cascading use of textile waste for the advancement of fibre reinforced composites for building applications. *J. Clean. Prod.* **2019**, *208*, 1524–1536. [CrossRef]
19. Glasper, M.J.; Picerno, G.; Tausif, M.; Russell, S.J. Closed loop mechanical recyclability of post-consumer waste wool fabrics based on fibre length retention. *Clean. Eng. Technol.* **2024**, *22*, 100796. [CrossRef]
20. Rahman, S.S.; Siddiqua, S.; Cherian, C. Sustainable applications of textile waste fiber in the construction and geotechnical industries: A retrospect. *Clean. Eng. Technol.* **2022**, *6*, 100420. [CrossRef]
21. Hadded, A.; Benltoufa, S.; Fayala, F.; Jemni, A. Thermo physical characterisation of recycled textile materials used for building insulating. *J. Build. Eng.* **2016**, *5*, 34–40. [CrossRef]
22. Rubino, C.; Liuzzi, S.; Martellotta, F.; Stefanizzi, P. Textile wastes in building sector: A review. *Model. Meas. Control. B* **2018**, *87*, 172–179. [CrossRef]
23. Patnaik, A.; Mvubu, M.; Muniyasamy, S.; Botha, A.; Anandjiwala, R.D. Thermal and sound insulation materials from waste wool and recycled polyester fibers and their biodegradation studies. *Energy Build.* **2015**, *92*, 161–169. [CrossRef]
24. Sengupta, S. Sound reduction by needle-punched nonwoven fabrics. *Indian J. Fibre Text. Res.* **2010**, *35*, 237–242.
25. Dissanayake, D.G.K.; Weerasinghe, D.U.; Wijesinghe, K.A.P.; Kalpage, K.M.D.M.P. Developing a compression moulded thermal insulation panel using postindustrial textile waste. *Waste Manag.* **2018**, *79*, 356–361. [CrossRef] [PubMed]
26. Korjenic, A.; Petránek, V.; Zach, J.; Hroudová, J. Development and performance evaluation of natural thermal-insulation materials composed of renewable resources. *Energy Build.* **2011**, *43*, 2518–2523. [CrossRef]
27. Wazna, M.E.; Gounni, A.; Bouari, A.E.; Alami, M.E.; Cherkaoui, O. Development, characterization and thermal performance of insulating nonwoven fabrics made from textile waste. *J. Ind. Text.* **2019**, *48*, 1167–1183. [CrossRef]
28. Pennacchio, R.; Savio, L.; Bosia, D.; Thiebat, F.; Piccablotto, G.; Patrucco, A.; Fantucci, S. Fitness: Sheep-wool and Hemp Sustainable Insulation Panels. *Energy Procedia* **2017**, *111*, 287–297. [CrossRef]
29. Berardi, U.; Iannace, G. Acoustic characterization of natural fibers for sound absorption applications. *Build. Environ.* **2015**, *94*, 840–852. [CrossRef]
30. Lee, Y.; Joo, C. Sound absorption properties of recycled polyester fibrous assembly absorbers. *Autex Res. J.* **2003**, *3*, 78–84. [CrossRef]
31. Buratti, C.; Belloni, E.; Lascaro, E.; Lopez, G.A.; Ricciardi, P. Sustainable Panels with Recycled Materials for Building Applications: Environmental and Acoustic Characterization. *Energy Procedia* **2016**, *101*, 972–979. [CrossRef]
32. Tiuc, A.-E.; Vermeşan, H.; Gabor, T.; Vasile, O. Improved Sound Absorption Properties of Polyurethane Foam Mixed with Textile Waste. *Energy Procedia* **2016**, *85*, 559–565. [CrossRef]
33. Zach, J.; Bubenik, J.; Novak, V.; Trisko, P. Development of acoustic insulating materials from recycled textile fiber. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *583*, 012018. [CrossRef]
34. Todor, M.P.; Bulei, C.; Kiss, I.; Cioată, V.G. Recycling of textile wastes into textile composites based on natural fibres: The reinforcement type and the architecture. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *477*, 012055. [CrossRef]
35. De Oliveira, E.M.; De Oliveira, E.M.; De Oliveira, C.M.; Dal-Bó, A.G.; Peterson, M. Study of the incorporation of fabric shavings from the clothing industry in coating mortars. *J. Clean. Prod.* **2021**, *279*, 123730. [CrossRef]
36. Peña-Pichardo, P.; Martínez-Barrera, G.; Martínez-López, M.; Ureña-Núñez, F.; Dos Reis, J.M.L. Recovery of cotton fibers from waste Blue-Jeans and its use in polyester concrete. *Constr. Build. Mater.* **2018**, *177*, 409–416. [CrossRef]
37. Pinto, J.; Peixoto, A.; Vieira, J.; Fernandes, L.; Morais, J.; Cunha, V.M.C.F.; Varum, H. Render reinforced with textile threads. *Constr. Build. Mater.* **2013**, *40*, 26–32. [CrossRef]
38. Reis, J.M.L.D. Effect of textile waste on the mechanical properties of polymer concrete. *Mat. Res.* **2009**, *12*, 63–67. [CrossRef]
39. Broda, J.; Brachaczek, W. Influence of Polypropylene Fibre Geometry on the Mechanical Properties of Cement Mortars. *Fibres Text. East. Eur.* **2015**, *23*, 123–129.

40. Spadea, S.; Farina, I.; Carrafiello, A.; Fraternali, F. Recycled nylon fibers as cement mortar reinforcement. *Constr. Build. Mater.* **2015**, *80*, 200–209. [CrossRef]
41. Briga-Sá, A.; Gaibor, N.; Magalhães, L.; Pinto, T.; Leitão, D. Thermal performance characterization of cement-based lightweight blocks incorporating textile waste. *Constr. Build. Mater.* **2022**, *321*, 126330. [CrossRef]
42. Algin, H.M.; Turgut, P. Cotton and limestone powder wastes as brick material. *Constr. Build. Mater.* **2008**, *22*, 1074–1080. [CrossRef]
43. Jaskuła, P.; Stienss, M.; Szydłowski, C. Effect of Polymer Fibres Reinforcement on Selected Properties of Asphalt Mixtures. *Procedia Eng.* **2017**, *172*, 441–448. [CrossRef]
44. Abtahi, S.M.; Sheikhzadeh, M.; Hejazi, S.M. Fiber-reinforced asphalt-concrete—A review. *Constr. Build. Mater.* **2010**, *24*, 871–877. [CrossRef]
45. Tang, C.; Shi, B.; Gao, W.; Chen, F.; Cai, Y. Strength and mechanical behavior of short polypropylene fiber reinforced and cement stabilized clayey soil. *Geotext. Geomembr.* **2007**, *25*, 194–202. [CrossRef]
46. Yetimoglu, T.; Salbas, O. A study on shear strength of sands reinforced with randomly distributed discrete fibers. *Geotext. Geomembr.* **2003**, *21*, 103–110. [CrossRef]
47. Tan, W.; Fu, F.; Wang, F.-F.; Li, Y.; Wang, P.; Zhang, D. The mechanical and ultraviolet aging properties of needle-punched nonwoven geotextiles made with recycled fibers. *J. Ind. Text.* **2022**, *51*, 8668S–8689S. [CrossRef]
48. Smith, C.W. *Nonwovens in Automotives—More than Just a Pretty Face*; Industrial Textile Associates: Greer, SC, USA, 2004; p. 6063.
49. Baskan, H.; Islk, B.; Erarslan, E.; Ejder, P.; Sezer, S.; Karakas, H. Design and Production of Tailored Rear Trunk Covering for Acoustic Applications. *IOP Conf. Ser. Mater. Sci. Eng.* **2018**, *460*, 012037. [CrossRef]
50. Atakan, R.; Karakaş, H.; Sezer, S.; İpek, S.; Aravi, İ.; Yıldırım, C.; Şen, E. Design of Nonwoven Carpets to Upgrade Sound Isolation Features in Automobiles. *Autex Res. J.* **2014**, *14*, 270–280. [CrossRef]
51. Atakan, R.; Sezer, S.; Karakas, H. Development of nonwoven automotive carpets made of recycled PET fibers with improved abrasion resistance. *J. Ind. Text.* **2020**, *49*, 835–857. [CrossRef]
52. Carvalho, D.; Ferreira, N.; França, B.; Marques, R.; Silva, M.; Silva, S.; Silva, E.; Macário, D.; Barroso, L.; Silva, C.J.; et al. Advancing sustainability in the automotive industry: Bioprepregs and fully bio-based composites. *Compos. Part C Open Access* **2024**, *14*, 100459. [CrossRef]
53. Ramamoorthy, S.K.; Persson, A.; Skrifvars, M. Reusing textile waste as reinforcements in composites. *J. Appl. Polym. Sci.* **2014**, *131*, 40687. [CrossRef]
54. Möhl, C.; Weimer, T.; Caliskan, M.; Baz, S.; Bauder, H.-J.; Gresser, G.T. Development of Natural Fibre-Reinforced Semi-Finished Products with Bio-Based Matrix for Eco-Friendly Composites. *Polymers* **2022**, *14*, 698. [CrossRef]
55. Montava-Jordà, S.; Torres-Giner, S.; Ferrandiz-Bou, S.; Quiles-Carrillo, L.; Montanes, N. Development of Sustainable and Cost-Competitive Injection-Molded Pieces of Partially Bio-Based Polyethylene Terephthalate through the Valorization of Cotton Textile Waste. *Int. J. Mol. Sci.* **2019**, *20*, 1378. [CrossRef]
56. Report Examines US Textile Recovery. Available online: https://www.recycle.com/latest/report-textile-recovery (accessed on 28 April 2024).
57. Wang, Y. Fiber and Textile Waste Utilization. *Waste Biomass Valor.* **2010**, *1*, 135–143. [CrossRef]
58. Shahid, M.A.; Habib, M.A.; Hossain, I.; Limon, M.G.M.; Islam, T.; Bhat, G. Eco-Friendly Jute-Based Hybrid Nonwoven Fabric for Packaging Applications. *ACS Omega* **2024**, *9*, 44639–44645. [CrossRef] [PubMed]
59. Heikkilä, P.; Määttänen, M.; Jetsu, P.; Kamppuri, T.; Paunonen, S. *Nonwovens from Mechanically Recycled Fibres for Medical Applications*; VTT Technical Research Centre of Finland: Espoo, Finland, 2020.
60. Biyada, S.; Urbonavičius, J. Circularity in textile waste: Challenges and pathways to sustainability. *Clean. Eng. Technol.* **2025**, *24*, 100905. [CrossRef]
61. Oliveira, C.; Carvalho, D.; Moura, I.; Ribeiro, B.; Ferreira, F. 3D Printing Using Natural Fibers—An Emerging Technology in Sustainable Manufacturing: A Review. In *Advanced Research in Technologies, Information, Innovation and Sustainability, Communications in Computer and Information Science*; Guarda, T., Portela, F., Diaz-Nafria, J.M., Eds.; Springer: Cham, Switzerland, 2024; pp. 343–356. [CrossRef]
62. Reif, M.; Zach, J.; Hroudová, J. Studying the Properties of Particulate Insulating Materials on Natural Basis. *Procedia Eng.* **2016**, *151*, 368–374. [CrossRef]
63. Abiola, O.S.; Kupolati, W.K.; Sadiku, E.R.; Ndambuki, J.M. Utilisation of natural fibre as modifier in bituminous mixes: A review. *Constr. Build. Mater.* **2014**, *54*, 305–312. [CrossRef]
64. Araújo, R.S.; Rezende, C.C.; Marques, M.F.V.; Ferreira, L.C.; Russo, P.; Emanuela Errico, M.; Avolio, R.; Avella, M.; Gentile, G. Polypropylene-based composites reinforced with textile wastes. *J. Appl. Polym. Sci.* **2017**, *134*, 45060. [CrossRef]