

Review

Sustainability-Oriented Innovation in the Textile Manufacturing Industry: Pre-Consumer Waste Recovery and Circular Patterns

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Abstract: The textile manufacturing industry is energy- and water-intensive, and has a great impact on the environment. Sustainability-oriented innovation can support the transition of the textile sector towards a circular economy. This review investigates how the textile manufacturing chain can benefit from sustainability-driven innovation strategies to achieve the main circular economy goals. The review was conducted using the Scopus and Web of Science scientific databases, and it addresses material, process, and organizational innovations and covers the 2015–2024 time window. Five main areas of innovation emerged from the retrieved papers, including digitalization, the need for innovative product and process design and sustainable raw materials, the use of textile waste as new raw material outside the textile value chain, waste recovery within the value chain and environmental remediation, and organizational innovation. The innovative solutions analyzed improve the sustainability of the textile manufacturing industry and enable the achievement of circular economy goals. Finally, we discuss some concerns about the introduction of the suggested innovations, including the need to apply design principles for recyclability and durability while studying the feasibility of adopting novel materials.

Keywords: sustainability; innovation; closed-loop recycling; circular economy; textile industry; pre-consumer waste recovery; water pollution



Academic Editors: Sergio Ulgiati, Cheng-Han Lee, Fan-Wei Liu and Hsing Jung Ho

Received: 20 December 2024

Revised: 27 February 2025

Accepted: 4 March 2025

Published: 5 March 2025

Citation: Butturi, M.A.; Neri, A.; Mercalli, F.; Gamberini, R. Sustainability-Oriented Innovation in the Textile Manufacturing Industry: Pre-Consumer Waste Recovery and Circular Patterns. *Environments* **2025**, *12*, 82. <https://doi.org/10.3390/environments12030082>

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1. Introduction

The textile industry is one of the industrial sectors that has the greatest impact on the environment and the use of resources. According to the Ellen MacArthur Foundation report “A new textiles economy: Redesigning fashion’s future” [1], total greenhouse gas emissions (GHG) from textile manufacture, at 1.2 billion tons per year, exceed those of all international flights and marine transportation combined. The textile manufacturing industry is energy-intensive: it uses both electricity to drive machinery and thermal energy for wet processing. Estimates report that the global average yearly specific energy consumption is about 16 MWh/t [2]. Furthermore, the textile industry utilizes around 215 trillion liters of water per year, making it the second-highest water use sector [3]. The extensive use of hazardous chemicals severely pollutes the waters, affecting ecosystems and human health [4].

The main environmental effect of textile goods originates in the manufacturing phases [5]. In addition to the fiber production process (both natural and synthetic), the later

spinning of yarns and weaving/knitting processes are sources of pollution and energy-intensive [6]. Moreover, a considerable amount of waste comes from scraps originating in cutting rooms throughout the garment production process (about 90–95% of total fabric waste), and the majority of this cutting room garbage is disposed of in landfills or incinerated [7,8]. Wet processing, dyeing, and finishing are the main sources of fresh water pollution [9]. Together with fiber and textile manufacturing, clothes distribution, usage, and disposal also contribute to the depletion of material resources and water and contaminate the environment, and the use of hazardous compounds endangers the health of textile workers and clothing consumers as well as the environment [10]. Along the textile supply chain (Figure 1), a significant quantity of solid waste materials is produced: in addition to shipping and packaging materials, various materials and components are discarded during the manufacturing processes, such as paperboard, plastics, stitching yarn, trims, fabric scraps, thread, metal clips, and others (it is estimated that about 12% of the total virgin feedstock is lost in the production phase [1]); pre-consumer waste includes damaged and unsold items, and post-consumer waste is the largest portion [11].

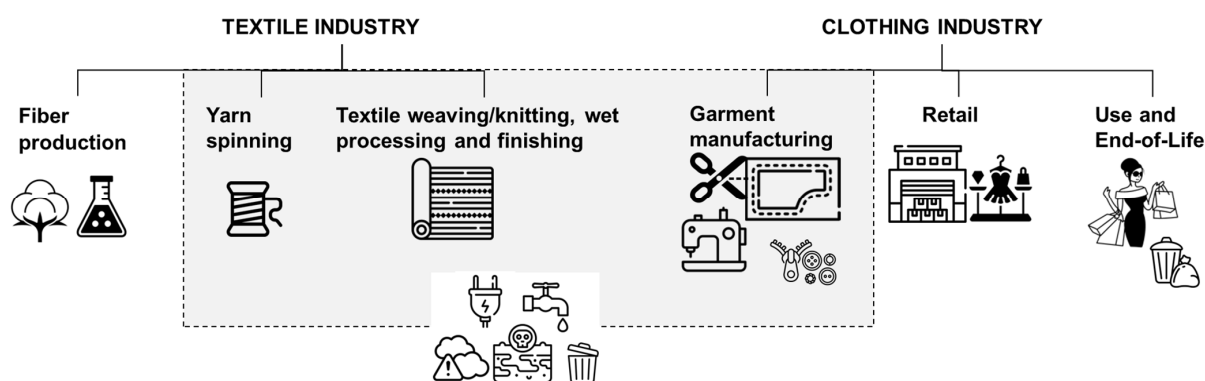


Figure 1. Simplified diagram of the textile supply chain. The environmental impacts of pre-consumer stages (excluding fiber production) are highlighted in terms of energy and water consumption; air, soil, and water pollution; and waste [4,9,12]. The packaging and transportation stages are excluded. The gray box identifies the focus of this paper.

Due to the complexity and variety of the textile manufacturing value chain, the average waste percentage data at each stage are highly dependent on the type of process, materials, available equipment, product design, country, etc. The cutting process is the most critical stage, since the amount of textile waste depends on the form and size of the pieces to be cut. As an example, a small textile mill in Thailand that produces traditional-style t-shirts, trousers, and skirts made of cotton and stitched with polyester yarn loses around 16.4% of its materials during the cutting process and 6.5% during the sewing process [13]. A textile factory based in Lithuania that manufactures cotton, wool, and mixed fabrics must manage 24% of waste materials after the cutting stage [14].

To make the textile supply chain more sustainable and circular, it is necessary to act at multiple levels incorporating the three major principles of circular economy (CE) [15]: (1) designing out waste, (2) keeping products and materials in use, and (3) regenerating natural systems. This can be summarized as follows [16]:

- improving product design to reduce the use of resources and polluting substances and facilitate the repair and reprocessing phase;
- extending the use phase, improving the quality of garments, and making consumers more aware;
- integrating end-of-life solutions into the value chain to facilitate reuse or reprocessing through process innovation

Some of the global fashion companies are already committed to implementing the circular economy objectives (see, for example, H&M and Patagonia [17,18]), showing that the pathway to circularity is challenging, but viable.

Considering the textile and clothing production stages, there are many options for reprocessing production waste. Fiber-based textile waste can be recyclable in the yarn-making processes (soft waste) or not (hard waste). Yarn-based wastage can be reused in textile processes, depending on fiber length, strength, cleanliness, and capability for homogeneous mixing/blending. The defective fabrics can be reconverted into yarns, or after chemical processing, the chemical-based fiber/yarn/fabric wastes are likely to be discarded [19].

Dyeing, printing, and the other wet processes, which use toxic chemicals, produce effluents that are challenging to treat because they include a variety of pollutants, both organic and inorganic, that, when released into the environment, severely degrade waters and ecosystems [20]. Solutions for minimizing wastewater generation and cost-effective treatments for reducing water contamination are compelling objectives. Textile wet processing units in developing or underdeveloped nations often lack the financial resources to purchase and operate costly machinery for wastewater management. As a result, effluents are released into the environment without proper treatment to ensure safety. This has resulted in serious environmental degradation near several of these facilities [20,21].

Closed-loop recycling pathways allow for greater material reuse, but at higher technological demands and processing costs [3]. On the other hand, according to Adams et al. [22], companies wishing to achieve sustainability-oriented innovation typically prioritize operational optimization and incremental innovation through technical adjustments to products and processes (e.g., reduced use of natural resources) to minimize environmental impact.

This research uses the literature review technique to identify which sustainability-driven innovations guide the transition of the textile and apparel manufacturing industry towards a circular economy. The analysis focuses on the pre-consumer waste management strategies, including waste recovery and effluent treatments, from a circular perspective (Figure 1). This boundary facilitates streamlined materials recovery operations and information flow, making upcycling more feasible, since pre-consumer waste streams are homogenous in composition and quality and can serve as raw material in the textile industry [23], while upcycling solutions for post-consumer textile waste are challenging due to the complexity of the supply chain and lack of information on the materials. Moreover, the selected boundary allows for taking a look at the textile manufacturing industry, with a focus on materials, processes, and technological and organizational innovations addressing the previously identified environmental issues.

Several previous reviews have focused on the sustainability-related challenges of the textile industry.

Some reviews focus on one specific innovation or theme. Hira and Alam [24] performed a bibliometric analysis of 324 papers on the textile industry's digital transformation. Jain and Kalapurackal [25] focus on the green practices applied to garment production.

Saha et al. [26] focus on identifying drivers and barriers to the transition to a circular economy of the whole textile supply chain; they notice that almost all research is based on the notion that technology-oriented circularity has a beneficial influence on sustainability. Desore and Narula [9] discuss the sustainability-related issues and responses of firms in the textile industry, considering consumers' behavior. Silina et al. [27] review policies and regulations facilitating the transition to a sustainable textile industry.

Many of the reviews miss the distinction between pre- and post-consumer textile waste, providing only a blurry picture of the potentially viable closed-loop patterns in the textile and clothing manufacturing sector. When considering the whole supply chain, in fact, the authors'

interest shifts to the challenging issues of complex reverse logistics, consumers’ behavior, and post-consumer textile waste recycling solutions and economics. Harsanto et al. [28] address aspects of innovation and sustainability, specifically from a business economics viewpoint, distinguishing only approximately between pre- and post-consumer strategies. De Ponte et al. [29] identified a set of best practices for improving the sustainability of the whole textile supply chain, including green chemistry approaches for recycling materials, the use of Industry 4.0 tools, and sustainable business models. Abbate et al. [30] analyze the whole supply chain, considering primarily organizational strategies. Moran et al. [31] consider the fashion industry, with a focus on fast-fashion issues and consumers’ behavior. Luján-Ornelas et al. [32] use a life cycle thinking approach to analyze sustainability in the textile industry, based on seven life cycle stages for textile products: fiber production, textile production, design, clothing production, commercialization, use, and end-of-life.

In order to fill this gap in the literature, this review aims to investigate how the manufacturing segment of the textile supply chain can benefit from sustainability-oriented innovation strategies to achieve the main circular economy goals by responding to the following research questions:

- R1. Which innovations have the potential to improve the sustainability of the textile manufacturing value chain?
- R2. How do they enable the achievement of circular economy objectives?

2. Methodology

This study uses the literature review methodology following the PRISMA flow diagram [33] to investigate the academic and peer-reviewed literature. The research of the papers was completed on 10 November 2024 using the Scopus and Web of Science (WoS) databases, due to their comprehensive coverage of peer-reviewed journals and high-quality conference proceedings. The identification of the papers was carried out using strings combining five keywords to focus the search on innovations and strategies leading to improved circularity in the textile manufacturing industry. The selected time window is 2015–2024, since it aims to investigate the most recent circular economy innovations starting in 2015, when United Nations (UN) Member States adopted the “2030 Agenda for Sustainable Development”, which includes the 17 Sustainable Development Goals (SDGs). Table 1 shows the approach adopted to identify and select the articles used in this review.

Table 1. Review protocol identification data.

Item	Description
Databases	Scopus, Web of Science
Keywords	Textile industry; sustainability; innovation; resource recovery; circular economy
Search fields	Title, Abstract, Keywords
Publication type	Journal and conference articles and reviews
Language	English
Time window	2015–2024
Other inclusion criteria	The articles focus on the textile/fashion manufacturing industry addressing sustainable solutions from a circular perspective
Exclusion criteria	The articles do not consider post-consumer waste textile, consumers’ behavior and fast fashion issues, the non-woven sector, e-textile, and social impacts

After the first search, 248 papers were identified. After removal of duplicates, all the papers identified as potential for review were analyzed through the keywords and abstracts to understand the content and verify if the results obtained could be useful for this study; therefore, in the content of the text, the inclusion and exclusion criteria were applied. In particular, only papers dealing with the manufacturing textile and apparel industry were selected, according to the boundary defined in Figure 1 (gray box). Articles were excluded if they focused on

- post-consumer textile waste since it requires the analysis of reverse logistics, involving a higher number of actors and more complex strategies, and raises additional technological issues deserving separate analysis;
- fast fashion issues that relate to consumers' behavior;
- the non-woven sector, which faces specific sustainability challenges and can be related to the reuse of post-consumer textile;
- e-textile, which hopefully will evolve sustainably, but currently it does not impact the sustainability of the existing textile manufacturing industry;
- social impacts, a theme often under-investigated and that poses specific geographical and ethical challenges and deserves a specific analysis.

The analysis of the entire text was confined to the residual papers only.

Finally, a further enrichment of the contributions was conducted through a backward snowballing process to identify additional relevant articles from the reference list of the selected articles. A total of 39 papers resulted from the complete review process (Figure 2).

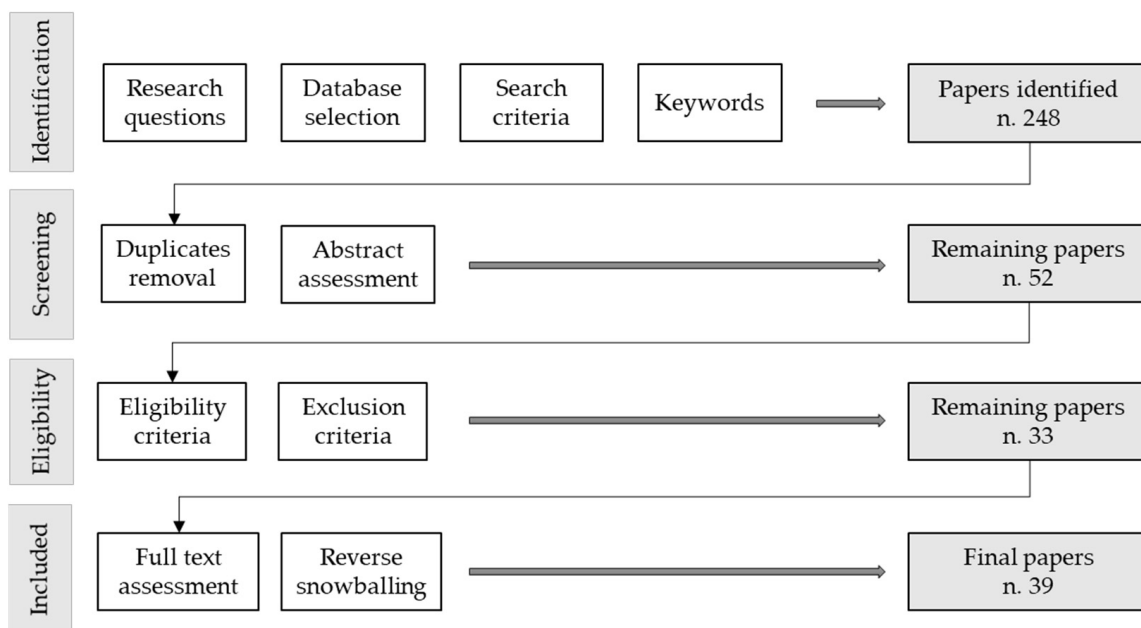


Figure 2. Development process of the review following the PRISMA flow diagram [33].

3. Results

The review results are provided using descriptive and thematic analysis.

3.1. Descriptive Analysis

The descriptive analysis provides a representative summary of the main characteristics of the selected articles, including year of publication, distribution across various journals, and the authors' geographic distribution.

3.1.1. Year of Publication

The number of published papers per year is presented in Figure 3.

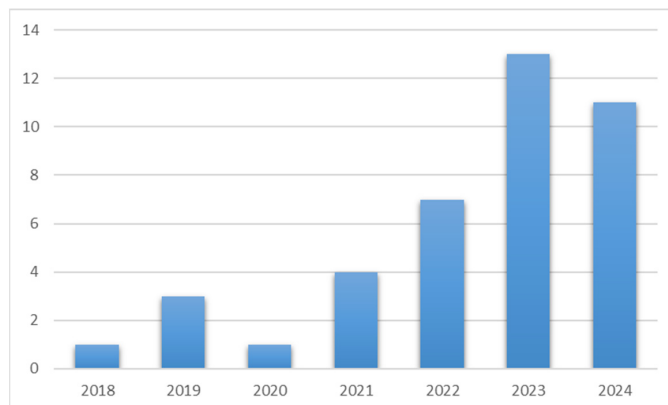


Figure 3. Yearly distribution of the reviewed papers.

Although the time frame in which the research was conducted started in 2015, the first selected articles are from 2018, after the Ellen MacArthur Foundation turned the spotlight on the circularity of the textile value chain with its report “A new textiles economy: Redesigning fashion’s future” [1]. This is most likely owing to the time required to develop and implement specific strategies congruent with those outlined by the UN Agenda, as well as the unification of the related terminology.

3.1.2. Distribution Across Journals

The 39 articles selected are distributed across 28 different journal titles, showing a wide interest in the transition to circularity of the textile industry. The Journal of Cleaner Production and Sustainability contained the highest number of publications, with six and five publications, respectively. The AUTEX Research Journal and Biomass Conversion and Biorefinery have two papers, while the other 24 journals only account for one article each, with more than 40 percent of the analyzed articles (n = 15) concentrated in 4 journals (Table A1).

3.1.3. Distribution by Region

The analysis of the authors’ geographic distribution is shown in Figure 4.

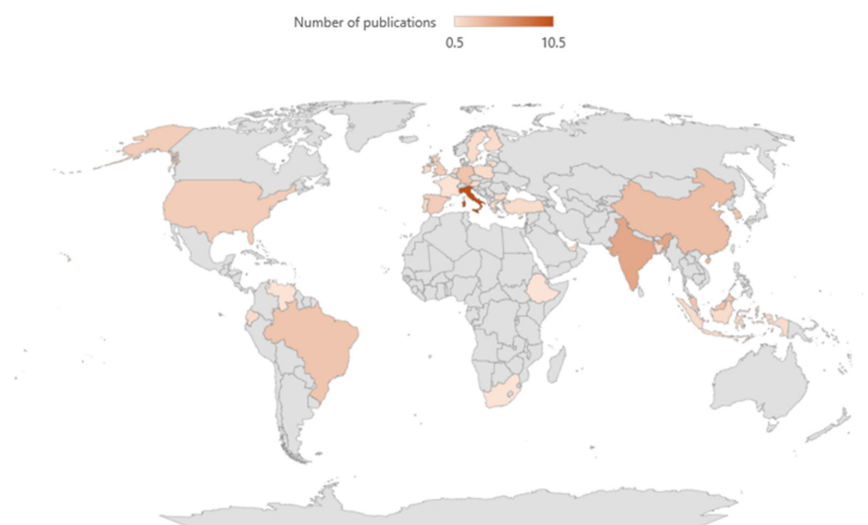


Figure 4. Geographical distribution of the reviewed articles obtained with the Excel map tool, considering the nationality of all the authors.

The origins of all authors were considered in the analysis by assigning fractional scores to authors of different nationalities.

The analysis of the data reveals that countries where the textile industry has a long history holding significant cultural importance, such as Italy and India, dominate the research on textile industry transition to a circular economy; however, academics from 30 countries contributed to the reviewed papers.

3.2. Thematic Analysis

The thematic analysis presents the relevant themes as they emerged from the reviewed papers and responds to the first research question.

Some empirical studies provide a global view on sustainability-oriented innovation strategies, emphasizing key concerns and limitations.

According to the database collected by Rese et al. [34] from news magazine articles and corporate communications, the majority of declared product innovations refer to clean products and materials recycling or are based on sustainable strategies (Figure 5).

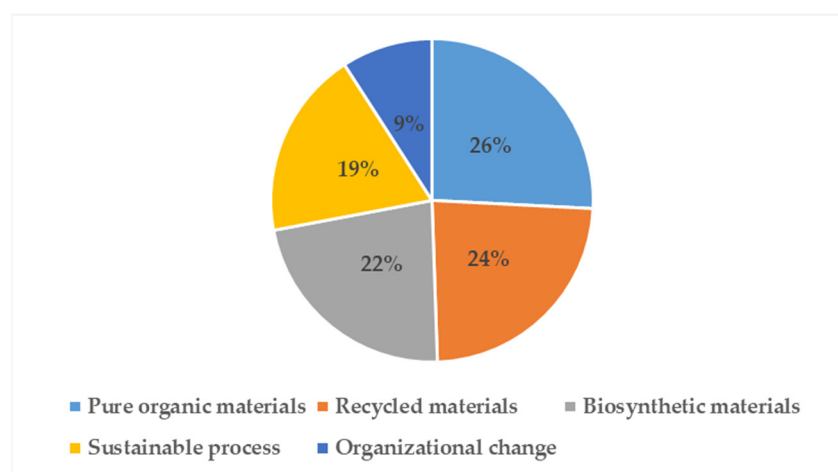


Figure 5. The percentage of innovations as classified by Rese et al. [27] and declared as product innovations by companies.

Dominidiato et al. [35] analyzed the sustainability-led innovation driven by the supplier–customer interdependence and interactions through a survey supplied to textile industry actors. Their findings underline that product innovation is primarily concerned with product durability and performance, recyclability, and the utilization of waste for new product development; process innovation is concerned with traceability, and water and chemical usage reduction. Harsanto et al. [28] classify sustainability innovation practices as product, process, and organizational innovation; the introduction of renewable and sustainable raw materials, enzymatic textile processing, and collaboration and business model innovation are essential aspects to be further investigated. The challenges to implementing sustainable innovation in the textile business are mainly cost, lack of expertise, lack of government backing, and macroeconomic concerns.

Ruan et al. [36], in their empirical study on 12 multinational apparel companies and their upstream manufacturers in China, found that adopting green management certification improved textile manufacturers' eco-efficiency, but it should be supported by the introduction of technological innovation that can enable eco-efficiency at a supply chain level, thanks to collaboration and greater availability of economic and human resources. Moreover, among the most urgent and impactful technological innovations, this study emphasizes the importance of reducing effluents and implementing effective wastewater treatment systems.

Siderius and Poldner [37] draw attention to the risk that approaches aimed at improving the circularity of the textile industry cause a rebound effect, which occurs when a certain technological improvement fails to deliver on its environmental promise owing to behavioral or economic causes. For example, strategies like introducing algae production for substituting fibers like cotton require more energy but less water, so an environmental tradeoff should be identified.

Completing the analysis of the papers, we identified five major areas of innovation aimed at enhancing the sustainability of the textile manufacturing industry. They can be described as follows: the introduction of digital technologies according to Industry 4.0 innovation patterns, the need for innovative product and process design and sustainable raw materials, the use of textile waste as new raw material outside the textile value chain, waste recovery within the value chain and environmental remediation, and systemic changes or business model innovation. Table A2 provides the match between papers and themes, where a tick indicates that the paper addresses the theme in the corresponding column. Multiple matches indicate a multi-perspective focus.

The following sub-sections detail the innovation areas.

3.2.1. Industry 4.0 and the Digital Transformation

Digital transformation is widely recognized as a key driver toward a circular economy. Digitalization of areas such as product design and prototyping and material recycling can improve the circularity of the textile industry, reducing its environmental impacts.

Due to their ability to process a large amount of data and make decisions quickly and effectively, artificial intelligence (AI) tools applied to textile manufacturing processes can enhance efficiency and product quality and optimize material use, reducing waste. AI tools are used in fiber development, yarn modeling and fabric assembly, design and defect detection, sales, and waste management [38]; blockchain technology improves traceability throughout the value chain [24,39]. AI tools applied to the manufacturing processes can enhance efficiency and product quality and reduce waste. A reinforcement learning approach (a branch of machine learning) is proposed by Lee et al. [40] for accurately predicting and reducing leftover dyes created in the dyeing and wet processing manufacturing stages, demonstrating an average reduction of 66.58% in dye residue over the two formulations tested; however, the authors observe that to generalize the performance of the model, more comprehensive training data are required. A framework for twin transition at the textile district level is proposed by Ferlito [41]; the empirical case demonstrates that cooperation at the district level can enable the implementation of Industry 4.0 technologies fostering circular business model innovation. Industry 4.0 innovations enable real-time monitoring, data analysis, and automation, which improves quality control throughout the value chain and the application of Lean and Six Sigma principles for process optimization and defect reduction [42].

The switch to digital manufacturing uses mathematics as a key enabling tool both for product and process innovation. Mathematical modeling applied to textile and garment design allows optimization of fabrication processes, reducing material waste, and customization of production on demand for shortening the supply chain [43]. VR technology and AI tools can enable personalized clothing production [44]. Larsson [5] analyzes some digital innovations for sustainable apparel systems: product configurator platforms for on-demand manufacturing to reduce overproduction (up to 30%); Kinetic garment construction, a design method that uses 3D virtual fitting and digital printing for automated cutting; and the use of conditional design to develop fully circular apparel products embedding IoT technologies to enable new uses for returned products and materials. The integration of IoT technologies within the Pakistani textile industry is discussed by Petrillo et al. [45] through

a small-scale pilot project. Different physical parameters were monitored through sensors (e.g., temperature, humidity, motion, GPS, light sensors) and displayed on a MATLAB 2020a graphic user interface. The collected real-time data were then analyzed to extract relevant information. The results demonstrate the potential for significant improvements in productivity, quality control, safety, and resource management, despite the financial and security constraints that may hinder the implementation of Industry 4.0 technologies.

RFID technology can improve the apparel supply chain at multiple levels. At the manufacturing level, it reduces processing time by approximately 12%, leading to a reduction of product loss. Moreover, helping to trace the fabric composition can improve the efficiency of fiber recycling and the share of recycled fibers that can be used in new textiles [7].

3.2.2. Design Innovations and Innovative Raw Materials

Raw materials coming from renewable or recycled resources are increasingly used as production alternatives to reduce resource depletion and improve processing procedures. In addition, according to the circular economy principles, closing the loop involves the integration of sustainable materials and design-driven strategies.

New material opportunities arise from the sectors of biotechnology and biofabrication: bacterial cellulose and polyhydroxyalkanoates (PHA), which are polyesters biosynthesized through bacterial cultures, lead to eco-friendly products [46]. However, companies involved in the new bio-based materials area are currently facing new issues, since many novel biomaterials, regardless of origin or manufacture, are further processed or blended with additional materials during the manufacturing process. These practices can have a significant impact on the circular dimension of the material itself, reducing its potential to be recycled and posing new challenges to designers [47]. The use of biodegradable materials for textile and apparel, materials that decompose into water, carbon dioxide, and biomass in the natural environment by physical, chemical, and microbiological processes, is investigated by Bao et al. [48]. Biodegradable bio-based fibers can be classified as bio-based natural fibers, bio-based regenerated fibers, and bio-based synthetic fibers. Aside from traditional natural fibers like cotton, whose production has a significant environmental impact, other natural fibers are now derived from agricultural by-products such as maize starch, soybean oil, or non-food cellulose, plant leftovers, and waste organic matter from agriculture and forestry. The application of petroleum-based biodegradable materials in the textile and apparel field is currently still limited, while natural and bio-based regenerated fibers are widely applied and show good biodegradability. These new biodegradable garment materials offer promising applications in the textile and garment industries, with some already being effectively used in garment items; however, their high cost restricts their use to the medical field. New bio-based synthetic fibers, made from natural plants chemically treated through microbial fermentation and genetic engineering to obtain high-purity monomers and then polymerized, are still under development.

Moran et al. [31] identify some brands and projects that use ocean waste (fishing nets and plastic bottles) to produce both fabrics (e.g., EcoAlf) and products (e.g., Adidas shoes). Recycled polyethylene terephthalate (PET) plastic bottles can be used to manufacture polyester fabrics. Recycled polyester has properties very similar to virgin polyester and a lower price and is suitable for producing scarfs (e.g., hijabs and Abayas). Using dry-dye technology instead of the conventional dyeing method allows for saving 90% of water and 85% of energy during the dyeing process [49].

Food waste valorization into regenerated protein fibers was demonstrated during World War II, due to resource scarcity, and then abandoned. According to Stenton et al. [50], it is still an interesting option once the required mechanical properties have been achieved and the sustainability of the recovery processes has been assessed.

Fu et al. [51] propose a method to create an extra layer, based on conjugated polymers from lysozyme (Lyz) and zwitterionic poly(sulfobetaine methacrylate) (pSBMA), with hydrophilic properties on top of a textile fabric to introduce stain resistance. This polymer nanofilm does not compromise the clothing comfort of the fabric and allows cleaning of the coated fabric only with water, minimizing the use of detergents. Thus, from the life cycle perspective, the extra cost of the treatment can be compensated by the savings at the use stage: the reduced need for cleanser products means both economic savings and reduced environmental impacts.

Using natural dyes as a substitute for synthetic ones is a way to mitigate the adverse environmental effects of textile dyeing and finishing wet processes [52]. Dyes derived from plant waste are being used to produce a collection of naturally dyed jeans by G Star Raw [31]. Agro-industrial waste and by-products are sustainable natural dye sources; however, natural dye adoption on an industrial scale is still hampered by issues like poor fastness qualities, low affinity for textile substrates, challenges with shade reproducibility, and other issues like cost-effectiveness or difficulty integrating natural dyes into existing industrial systems [53].

Rahaman et al. [54] suggest the use of environmentally friendly nanomaterials, such as biodegradable and bio-based nanoparticles, to improve the quality of fabrics and their functional performance, such as stain resistance, durability, and self-cleaning properties.

3.2.3. Waste Recovery Within the Value Chain and Environmental Remediation

The manufacturing phase of the textile industry produces both textile waste and effluents. Since the textile industry is water-intensive and causes severe water pollution due to wet and dyeing processes, wastewater treatment is necessary for both environmental protection and reuse. Textile wastewater can contain suspended particles, oil, grease, gritty materials, organic substances, surfactants, heavy metals, color, and sulfates, so that it requires up to three treatment stages [55]. The adoption of the innovative zero liquid discharge (ZLD) technology ensures the minimization of water discharge, allowing the reuse of treated water [56]. ZLD combines the use of different technologies, such as reverse and forward osmosis, ultra-filtration, thermal processes (multi-effect evaporator and forced evaporator), and crystallizing. The ZLD technology is implemented in Europe and North America, but it is still in the introduction phase in countries like India, South Korea, and China. Mikuciuniene et al. [51] identified several areas of innovation related to textile wet processes and water treatments that need to be further investigated, including the use of eco-friendly chemicals, the reuse of treated water, and the recovery of resources from wastewater.

Textile dyes impair the quality of bodies of water and aquatic vegetation, potentially affecting human health. Inefficient textile dyeing procedures result in 15–50% of azo dyes being discharged into wastewater. The presence of dyes and textile pigments in wastewater results in a highly colorful solution with variable pH and high levels of biological oxygen demand (BOD), chemical oxygen demand (COD), total organic carbon (TOC), and suspended particles. Some textile facilities cleanse their wastewater to degrade the free azo dyes discharged into the environment, whereas others dump untreated industrial effluents straight into bodies of water, posing major ecotoxicological hazards. Moreover, because of the great durability and solubility of synthetic dyes in water, standard treatment solutions are typically ineffectual, requiring the adoption of advanced technologies. No particular treatment technology is acceptable or globally applicable for all types of textile effluents. As a result, the treatment of textile wastewater involves a combination of physical, chemical, and biological treatments, depending on the kind and quantity of pollutant load (Table 2) [21,57].

Table 2. Approaches for textile dye wastewater treatment (based on [21]).

Approach	Technology	Description	Advantages/Drawbacks
Physical	Adsorption	Adsorbed molecules or ions are attracted to a solid adsorbent surface (zeolites, alumina, silica gel, activated carbon)	Reusability of adsorbents, high efficiency, short time of treatment
	Ion exchange	Separation is achieved by generating strong bonds between the resins used in a packed bed reactor and the solutes	Low cost, regeneration, simplicity, flexibility, high efficiency
	Membrane filtration	The membranes have small pores, so solutes larger than these pores are trapped; nano-filtration technology also uses electrostatic repulsion mechanisms; ultrafiltration removes organic dyes; reverse osmosis (RO) membrane	Simple and effective; the membranes need periodic replacement RO technology allows separation with no state change or thermal energy
Chemical	Coagulation -flocculation	Metal salts and polymers can be used as coagulants, while flocculants are polymers increasing the aggregation of flocs so that they can be separated more easily	Cost-effective, pH-dependent, and producing concentrated sludge
	Advanced oxidation	Based on the in situ generation of hydroxyl radicals (OH [•]), which are powerful oxidizing agents; photocatalysis, Fenton, photo-Fenton, ozonation, and electrochemical oxidation	Suitable for harsh conditions, quick and without the formation of sludge; expensive, pH-dependent, producing toxic by-products
	Electrochemical	Electrocoagulation, electro-Fenton (oxidation and coagulation), anodic oxidation	Does not require the addition of chemicals and produces no sludge; high electricity costs
Biological	Enzyme-assisted degradation	To convert dye molecules into non-toxic products	Industrial enzymes: low cost, efficient, reliable, available in liquid form
	Bacteria-assisted degradation	100% efficiency in dye-containing textile wastewater biodegradation, and bacterial consortia frequently outperform a single strain in dye removal effectiveness	Ease of cultivation, high specific growth, versatile catalytic capability for mineralizing azo dyes
	Fungal-assisted degradation	Degradation and mineralization	Ability to accelerate their metabolism in order to achieve optimal environmental conditions
	Yeast-assisted degradation	Biosorption and reductive azo bond cleavage	Rapid growth rates, suitable for adverse environmental conditions

According to the critical review of Al-Tohamy et al. [21] discussing the treatment of the dye-containing wastewater, biological approaches are more effective than physical and chemical methods due to their ease of application, reduced sludge production, lower cost, energy-saving features, environmental safety, and non-toxic by-products. This makes biological techniques suitable for application in developing nations. In this context, Marovska et al. [58] show that employing industrial rose and lavender solid by-products as adsorbents, together with further degradation of the post-adsorption plant biomass by higher fungi, may effectively decontaminate water and remove the azo dye Acid Orange 7, which is primarily used in silk and wool dyeing. A novel biodegradation process of soil pollutants from dyes using a bacterium allows for environmental decontamination [29].

Typically, residuals fabrics and leftover filaments in spools are considered a negative item on companies' balance sheets; creating new uses or target markets should be a primary goal to achieve a circular business model [35]. Textile production scraps can be recycled using enzymes and biocatalysts, bringing about a specific biochemical reaction. Since most of the man-made fibers are multi-material compositions, enzymes can be used to catalyze the breakdown of polymers into monomers, enabling circular economy-based recycling processes for multi-material textiles [59].

The sustainability of regenerated fibers is the main topic of the review compiled by Kim et al. [60]. Raw materials, such as traditional cellulose sources or low-value feedstock, recycled textiles, and microbiological matter, are regenerated to produce solid fibers that are integrated into textile products. The resultant textile products can be recycled as source materials for producing regenerated fibers or biodegraded into tiny molecules and returned to nature. However, the sustainability-related advantages are still uncertain due to insufficient analysis and lack of a standardized methodology to evaluate the environmental impacts of the regenerated fibers.

Bressanelli et al. [61] analyzed the structured cooperation along the textile supply chain into the Prato (IT) district, finding virtuous examples of materials recovery, including a wool regeneration business that uses chemical-free and dye-free processes on scraps and leftovers generated by garment makers from spinning to the finishing phase; a regenerated yarns manufacturer; and a start-up designing and manufacturing fully recyclable garments produced from regenerated fibers.

3.2.4. Textile Waste as New Raw Material (Outside the Textile Value Chain)

Several studies have summarized the primary uses of textile and garment waste as reinforced composites, such as reinforced polyethylene matrix for soil reinforcement and brick making, adsorbent fiber for heavy metal adsorption, chipboard production, lightweight polymer concrete as aggregate, activated carbon, and thermal insulation material [62].

Waste sheep-wool fibers can be incorporated into polymer composites for applications in diverse fields, including construction materials and automotive and packaging materials [63]. Wool fibers' structural qualities—such as their high aspect ratio, surface morphology, and chemical makeup—help improve the composites' mechanical, thermal, and flame-retardant qualities.

3.2.5. Organizational Strategies and Business Model Innovation

Many authors highlight the need for systemic change in the textile industry to become more circular [34]. Sustainable strategies include investing in sustainable materials, managing the flow of materials, collaborating with stakeholders, tracking progress, and reporting sustainability performance. Battesini Teixeira et al. [64] developed a methodology for circular thinking in the textile industry, focusing on stakeholder integration, raw material sustainability, and design for remanufacturing and recycling.

Arnold et al. [65], in their survey of 56 German textile firms, discovered that many manufacturing textile companies are not yet equipped for a circular transformation, with just a few implementing strategies such as material innovation and the use of waste textile as new raw material. Ermini et al. [66] introduced a novel process model for sustainability-oriented innovation in small and medium enterprises based on supply network orchestration, which leads to a circular business model.

4. Discussion

The textile manufacturing industry is facing major sustainability challenges due to its severe impacts on the environment. Besides incremental process improvement, which

involves implementing the best available techniques (BAT) [67] such as those provided by the European Bureau for Research on Industrial Transformation and Emissions, many innovations are being developed to be applied at the product, process, and organizational levels to reduce the textile manufacturing industry’s environmental footprint. The sustainability-oriented innovations retrieved from the literature are mainly focused on the most critical aspects of the textile and apparel manufacturing industry: resources and materials, the effluents produced in the wet processing and dyeing steps, and pre-consumer waste management and recovery.

This section discusses how the innovative solutions analyzed enable the achievement of circular economy goals and improve the sustainability of the textile manufacturing value chain, supporting the implementation of UN Sustainable Development Goals. Lastly, the open issues and future research directions are discussed.

4.1. Circular Economy Goals Achievement

Table 3 summarizes the CE objectives achievable thanks to the described sustainability-oriented innovations and responds to the second research question.

Table 3. Circular economy goals achievable through the implementation of the retrieved sustainability-oriented innovations.

SOI ¹ Area	CE Enabling Innovation	CE Objective
Industry 4.0 and digitalization	Process optimization (AI, IoT); Customization (3D virtual fitting, digital printing, AI, VR)	Waste reduction and recycling
	Traceability (IoT, Blockchain, RFID)	
Design innovations and innovative raw materials	Bio-based raw materials; natural dyes	Pollution reduction
	Recycled raw materials; novel processes	Resource saving
Waste recovery within the value chain and environmental remediation	Wastewater treatment	Pollution reduction
	Contaminated soil and water treatment	Environmental remediation
	Textile production waste recovery	Waste reduction and recycling
Textile waste as new raw material (outside the value chain)	Textile (production) waste recovery	Waste reduction and recycling
Organizational strategies and Business model innovation	Circular thinking strategies; sustainability reporting; collaboration along the supply chain	Waste reduction; remanufacturing and recycling; resource saving
	Sustainable and recycled materials	Resource saving; waste reduction

¹ Sustainability-oriented innovation.

Innovations from different thematic areas can contribute together to CE objectives, interacting synergistically. For example, digital transformations and organizational strategies can support all other innovations.

The first CE principle, “eliminate waste and pollution”, is supported by the introduction of advanced digital tools, the use of renewable and natural materials, waste management and recovery processes, and the application of circular thinking strategies and collaboration along the supply chain.

The use of advanced digital tools supports waste reduction along the whole value chain, enhancing the efficiency of the processes and material and product quality. Using 3D virtual fitting and digital printing in the cutting phase allows for scrap reduction and 10% material savings [5]. The use of new eco-compatible materials, such as natural fibers derived from agricultural by-products and natural dyes, can reduce environmental pollu-

tion. The application of circular thinking strategies promotes virtuous waste management and recovery actions, also creating cooperation among different actors belonging to the textile manufacturing supply chain.

The second CE principle, “circulate products and materials”, is mainly supported by the textile waste recovery in new products, inside or outside the textile value chain. When textile scraps are multi-material, a natural process using enzymes can accelerate the breakdown of polymers into monomers, allowing for remanufacturing operations. Textile waste remanufacturing is also supported by the traceability of materials, which can be fostered by the use of digital tools like blockchain and IoT technologies. The use of recycled materials is a corporate strategy consistent with this CE principle, fostering product and process design innovations.

Lastly, the third CE principle, “regenerate nature”, is supported by innovative solutions for treating polluted water and soil, such as bioremediation technologies that utilize organisms like bacteria to neutralize pollutants.

4.2. Support for the UN Sustainable Development Goals Implementation

Many efforts are requested of the global textile and apparel supply chain to comply with the UN SDGs [68,69]. The retrieved sustainability-oriented innovations affecting the manufacturing textile industry can contribute to implementing SDGs mainly related to economic and environmental sustainability.

In particular, SDG 12, “Responsible Consumption and Production Patterns”, includes ecologically friendly production practices, such as decreasing textile waste and implementing circular fashion business models. All the reviewed practices linked to digital transformation, design for recyclability, textile production waste recovery, as well as organizational and business model innovations support the improvement of textile industry circularity and ecological footprint. The innovative production practices promoted by digitalization, design innovations and new materials, and new organizational strategies contribute to SDG 9, “Industry, innovation and Infrastructure”, promoting sustainable innovations. Cooperation along the textile manufacturing supply chain promotes both SDG 9 and SDG 17, “Partnership for the Goals”, grouping together the different actors sharing the same sustainability-related objectives.

Digital tools, design and material innovations aimed at optimizing the processes and water consumption and reducing their impacts on the water reserves, as well as water treatment innovations support SDG 6, improving access to “clean water and sanitation”. Novel and optimized processes also contribute to the achievement of SDG 13, calling for “Climate action”, since they allow for energy savings and reduced carbon emissions.

Although energy issues have not clearly emerged from the research carried out, the decarbonization of the textile manufacturing industry should be enhanced using energy-efficient machines combined with renewable energy technologies, supporting the achievement of SDG 7, “Affordable and Clean Energy” [70]. In addition, social innovations, which are not considered in this study, are of fundamental importance to accomplish SDG 8, “Decent Work and Economic Growth,” which is connected to the negative consequences of mass manufacturing at reduced costs, widespread in poor nations with unsafe working conditions.

4.3. Open Issues and Future Research Directions

Some concerns emerged from the literature regarding the introduction of the proposed innovations, suggesting future research directions.

The feasibility of adopting novel materials should be complemented by the application of design for recyclability and durability principles. Similarly, the environmental (and

social) implications of innovative solutions and processes should be assessed concurrently with their development [23]. Therefore, together with materials' availability and the techno-economic feasibility, the environmental impacts of agricultural by-product recovery processes must be assessed. In addition, when developing innovative biodegradable materials, it is important to examine the procedures that textiles must undergo during manufacture, since they might alter their biodegradation qualities [71].

The need for advanced wastewater treatments, like ZLD, whose approach depends on the properties of the wastewater produced by the diverse manufacturing processes [72], clashes with the costs of the facilities, especially in countries with fewer resources. Therefore, the development of increasingly effective techniques must always be accompanied by cost analysis [57]. In addition, ZLD systems require significant energy input, potentially leading to increased operational costs and footprint (see, for example, Buljan et al. [73]). The techno-economic feasibility of the ZLD approach has been demonstrated in India, where some pilot-scale plants integrate renewable technologies like solar evaporators or pellet reactors to cut costs [72]. In addition, the environmental benefits of the ZLD approach extend beyond water reuse, as an essential goal of ZLD is to recover chemicals used during the whole textile manufacturing process. As a result, the economics of the ZLD process must also consider the savings from chemical recovery [74].

Still referring to developing countries, the textile industry's lack of wastewater treatment infrastructure has significantly polluted the environment, with serious consequences for human health. The principle of nature remediation, a concept that goes beyond the previous one of preservation, is crucial here, and the textile industry should recognize its responsibility and implement remediation processes.

Industry 4.0 technologies can support eco-friendly practices, improving process efficiency and reducing waste; however, their implementation faces some barriers, mainly when involving small and medium enterprises (SMEs). In fact, it is apparent that SMEs want to implement these technologies; nevertheless, SMEs suffer from more financial and knowledge resource restrictions than multinational corporations [75]. In addition, it is essential considering that digital technologies like AI are directly responsible for carbon emissions from the use of non-renewable energy to power computing machines and the usage of fresh water for data center cooling. Improvements in hardware and AI models' efficiency can lower energy costs; however, improved efficiency can lead to higher demand for AI, thus raising, rather than lowering, overall resource utilization (rebound effect) [76].

Among the organizational strategies, various authors emphasize that cooperation between the different actors across the supply chain fosters the implementation of closed-loop recycling routes. Sharing knowledge and infrastructure with other companies and research institutions is crucial for improving waste management and recovery [3]. Companies recycling and remanufacturing the available textile waste in the Prato district [61] are virtuous examples of coordination among businesses, guaranteeing a constant and secure supply of waste materials. In addition, cooperation along the supply chain can allow for a more accurate quantification of scope 3 emissions [23]. The industrial symbiosis (IS) approach, involving different companies in a coordinated network for exchanging resources and waste streams, can support this strategy [77]. IS can also support the creation of synergies between different industries when textile waste can be used as raw material for another process. This circular model can be realized for using textile waste as reinforced composites and for the adsorption of Acid Orange 7 in polluted water using the rose and lavender industrial by-products while producing harmless mycelium-based bio-composites [58].

5. Conclusions

This review analyses the sustainability-oriented innovations that are driving the transition of the textile and apparel manufacturing industry towards a circular economy. The focus is on pre-consumer waste management strategies, including waste recovery and effluent treatments, since these waste streams are homogeneous in content and quality and can remain within the textile industry as raw material.

The analysis of the articles allowed us to identify five major areas of innovation aimed at enhancing the sustainability of the textile manufacturing industry: digitalization according to Industry 4.0 innovation technologies, innovatively designed raw materials, waste recovery within the value chain and environmental remediation, the use of textile waste as new raw material outside the textile value chain, and organizational innovation. All the innovation areas support the transition towards the circular economy of the textile industry, allowing the achievement of CE goals and supporting the implementation of UN Sustainable Development Goals.

Future research directions are suggested by some critical issues revealed by the review: the need for the systematic use of design for recyclability and durability principles while investigating the viability of using innovative materials. Similarly, the environmental consequences of creative solutions should be evaluated concurrently with their development. Moreover, it is worth looking into the feasibility of the industrial symbiosis approach for textile waste management. Lastly, the social impacts of sustainability-oriented innovations in the textile manufacturing industry and social innovations require further, in-depth analysis.

Author Contributions: Conceptualization, M.A.B. and F.M.; methodology, M.A.B. and F.M.; software, F.M.; validation, M.A.B., A.N. and R.G.; formal analysis, M.A.B.; investigation, F.M.; resources, A.N.; data curation, F.M. and M.A.B.; writing—original draft preparation, F.M. and M.A.B.; writing—review and editing, M.A.B., A.N. and R.G.; visualization, F.M. and A.N.; supervision, M.A.B. and A.N.; project administration, R.G.; funding acquisition, R.G. All authors have read and agreed to the published version of the manuscript.

Funding: This project is partially funded by the ESF REACT-EU: Programma Operativo Nazionale (PON) “Ricerca e Innovazione” 2014–2020, CCI2014IT16M20P005, Progetti DM 1062 del 10 Agosto 2021.

Data Availability Statement: Not applicable.

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

Appendix A

Table A1. Paper distribution across journals.

Journal	Number of Papers
Journal of Cleaner Production	6
Sustainability	5
AUTEX Research Journal	2
Biomass Conversion and Biorefinery	2
Research Journal of Textile and Apparel	1
Waste Management & Research: The Journal for a Sustainable Circular Economy	1
Competitiveness Review: An International Business Journal	1
The Journal of the Textile Institute	1
Environmental Science and Pollution Research	1
Applied Sciences	1
Nano-Structures & Nano-Objects	1
Sustainable Production and Consumption	1

Table A1. *Cont.*

Journal	Number of Papers
International Journal of Precision Engineering and Manufacturing-Green Technology	1
Advances in Science and Technology	1
Journal of Business & Industrial Marketing	1
Vision: The Journal of Business Perspective	1
International Journal on Interactive Design and Manufacturing	1
Molecules	1
Nature Sustainability	1
SN Applied Sciences	1
Journal of Material Cycles and Waste Management	1
Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences	1
Sustainable Chemistry and Pharmacy	1
Ecotoxicology and Environmental Safety	1
Journal of Environmental Management	1
International Journal of Recent Technology and Engineering	1
International Journal of Production Economics	1
Sustainable Environment	1

Table A2. Literature review: research trends and theme classification.

Authors, Year, and Ref.	Industry 4.0	Product/ Process Design and Resources IN ¹	Resources OUT ¹	Waste Recovery ¹ and Environmental Remediation	Business Model
Larsson, 2018, [5]	✓				
Piribauer and Bartl, 2019, [59]				✓	
Gupta et al., 2019, [49]		✓			
Denuwara et al., 2019, [7]	✓				
Kędzia and Dziuba, 2020, [44]	✓				
Provin et al., 2021, [46]		✓			
Moran et al., 2021, [31]		✓			
Stenton et al., 2021, [50]		✓			
Siderius and Poldner, 2021, [37]		✓			✓
Kim et al., 2022, [60]		✓		✓	
Rese et al., 2022, [34]		✓			✓
Bressanelli et al., 2022, [61]				✓	✓
D'Itria and Colombi, 2022, [47]		✓			
Ruan et al., 2022, [36]			✓		✓
Al-Tohami et al., 2022, [21]			✓		✓
Magri and Ciarletta, 2023, [43]	✓	✓			
De Ponte et al., 2023, [29]		✓			✓
Harsanto et al., 2023, [28]		✓	✓	✓	✓
Arnold et al., 2023, [65]	✓				✓
Fu et al., 2023, [51]		✓			✓
Sharma and Singh, 2023, [42]	✓				✓
Hira and Alam, 2023, [24]	✓				
Dominidiato et al., 2023, [35]		✓	✓		✓
Battesini Teixeira et al., 2023, [64]		✓			✓
Pizzicato et al., 2023, [53]		✓			
Chand et al., 2023, [62]			✓	✓	
Kulkarni et al., 2023, [63]			✓		
Ramos et al., 2023, [39]	✓				
Gorse et al., 2024, [52]		✓			
Rahaman and Kahn, 2024, [54]		✓			
Petrillo et al., 2024, [45]	✓				
Pundir et al., 2024, [56]				✓	
Bao et al., 2024, [48]		✓			
Mikucioniene et al., 2024, [55]		✓		✓	
Ferlito, 2024, [41]	✓			✓	
Marovska et al., 2024, [58]				✓	
Lee et al., 2024, [40]	✓				
Ermini et al., 2024, [66]					✓
Saha et al., 2024, [26]	✓	✓	✓	✓	

¹ Resources IN: new and sustainable raw materials to be used inside the textile value chain; Resources OUT: recovered materials to be used outside the textile value chain; waste recovery inside the textile value chain.

References

1. Ellen MacArthur Foundation A New Textiles Economy: Redesigning Fashion's Future. 2017, pp. 1–150. Available online: <http://www.ellenmacarthurfoundation.org/publications> (accessed on 10 December 2024).
2. Kousar, S.; Shafqat, U.; Kausar, N.; Pamucar, D.; Karaca, Y.; Salman, M.A. Sustainable Energy Consumption Model for Textile Industry Using Fully Intuitionistic Fuzzy Optimization Approach. *Comput. Intell. Neurosci.* **2022**, *2022*, 5724825. [[CrossRef](#)] [[PubMed](#)]
3. Huang, X.; Tan, Y.; Huang, J.; Zhu, G.; Yin, R.; Tao, X.; Tian, X. Industrialization of open- and closed-loop waste textile recycling towards sustainability: A review. *J. Clean. Prod.* **2024**, *436*, 140676. [[CrossRef](#)]
4. Oliveira Neto, G.C.d.; Cesar da Silva, P.; Tucci, H.N.P.; Amorim, M. Reuse of water and materials as a cleaner production practice in the textile industry contributing to blue economy. *J. Clean. Prod.* **2021**, *305*, 127075. [[CrossRef](#)]
5. Larsson, J.K.J. Digital innovation for sustainable apparel systems: Experiences based on projects in textile value chain development. *Res. J. Text. Appar.* **2018**, *22*, 370–389. [[CrossRef](#)]
6. Shirvanimoghaddam, K.; Motamed, B.; Ramakrishna, S.; Naebe, M. Death by waste: Fashion and textile circular economy case. *Sci. Total Environ.* **2020**, *718*, 137317. [[CrossRef](#)]
7. Denuwara, N.; Maijala, J.; Hakovirta, M. Sustainability benefits of RFID technology in the apparel industry. *Sustainability* **2019**, *11*, 6477. [[CrossRef](#)]
8. Dissanayake, D.G.K.; Weerasinghe, D. Managing post-industrial textile waste: Current status and prospects for Sri Lanka. *J. Text. Inst.* **2021**, *112*, 1804–1810. [[CrossRef](#)]
9. Desore, A.; Narula, S.A. An overview on corporate response towards sustainability issues in textile industry. *Environ. Dev. Sustain.* **2018**, *20*, 1439–1459. [[CrossRef](#)]
10. Manshoven, S.; Christis, M.; Vercalsteren, A.; Arnold, M.; Nicolau, M.; Lafond, E.; Mortensen, L.F.; Coscieme, L. *Eionet Report—ETC/WMGE 2019/6 Textiles and the Environment in a Circular Economy*; European Environment Agency (EEA): Copenhagen, Denmark, 2019.
11. Nyika, J.; Dinka, M. Sustainable management of textile solid waste materials: The progress and prospects. *Mater. Today Proc.* **2022**, *62*, 3320–3324. [[CrossRef](#)]
12. Roy Choudhury, A.K. Environmental impacts of the textile industry and its assessment through life cycle assessment. In *Roadmap to Sustainable Textiles and Clothing, Environmental and Social Aspects of Textiles and Clothing Supply Chain*; Springer Science+Business Media: Singapore, 2014; ISBN 9789812871107.
13. Kasemset, C.; Chernsupornchai, J.; Pala-Ud, W. Application of MFCA in waste reduction: Case study on a small textile factory in Thailand. *J. Clean. Prod.* **2015**, *108*, 1342–1351. [[CrossRef](#)]
14. Rapsikevičienė, J.; Gurauskienė, I.; Jučienė, A. Model of industrial textile waste management. *Environ. Res. Eng. Manag.* **2019**, *75*, 43–55. [[CrossRef](#)]
15. Ellen MacArthur Foundation. Available online: <https://www.ellenmacarthurfoundation.org/> (accessed on 10 December 2024).
16. Abdelmeguid, A.; Afy-Shararah, M.; Saloni, K. Towards circular fashion: Management strategies promoting circular behaviour along the value chain. *Sustain. Prod. Consum.* **2024**, *48*, 143–156. [[CrossRef](#)]
17. H&M. Available online: <https://hmgroupp.com/sustainability/circularity-and-climate/circularity/> (accessed on 31 January 2025).
18. Patagonia. Available online: <https://www.patagonia.com/stories/our-quest-for-circularity/story-96496.html> (accessed on 31 January 2025).
19. Mishra, P.K.; Izrayeel, A.M.D.; Mahur, B.K.; Ahuja, A.; Rastogi, V.K. A comprehensive review on textile waste valorization techniques and their applications. *Environ. Sci. Pollut. Res.* **2022**, *29*, 65962–65977. [[CrossRef](#)] [[PubMed](#)]
20. Madhav, S.; Ahamad, A.; Singh, P.; Mishra, P.K. A review of textile industry: Wet processing, environmental impacts, and effluent treatment methods. *Environ. Qual. Manag.* **2018**, *27*, 31–41. [[CrossRef](#)]
21. Al-Tohamy, R.; Ali, S.S.; Li, F.; Okasha, K.M.; Mahmoud, Y.A.G.; Elsamahy, T.; Jiao, H.; Fu, Y.; Sun, J. A critical review on the treatment of dye-containing wastewater: Ecotoxicological and health concerns of textile dyes and possible remediation approaches for environmental safety. *Ecotoxicol. Environ. Saf.* **2022**, *231*, 113160. [[CrossRef](#)]
22. Adams, R.; Jeanrenaud, S.; Bessant, J.; Denyer, D.; Overy, P. Sustainability-oriented Innovation: A Systematic Review. *Int. J. Manag. Rev.* **2016**, *18*, 180–205. [[CrossRef](#)]
23. Chopra, S.S.; Dong, L.; Kaur, G.; Len, C.; Ki Lin, C.S. Sustainable process design for circular fashion: Advances in sustainable chemistry for textile waste valorisation. *Curr. Opin. Green Sustain. Chem.* **2023**, *39*, 100747. [[CrossRef](#)]
24. Hira, F.A.; Alam, M.M. A Bibliometric Research Trend Analysis on Emerging Technology in the Textile Industry. *Vision* **2023**, *0*, 1–17. [[CrossRef](#)]

25. Jain, S.; Kalapurackal, J.J. A Systematic Review of Green Apparel Manufacturing. *Environ. Res. Eng. Manag.* **2023**, *79*, 124–133. [[CrossRef](#)]
26. Saha, K.; Dey, P.K.; Kumar, V. A comprehensive review of circular economy research in the textile and clothing industry. *J. Clean. Prod.* **2024**, *444*, 141252. [[CrossRef](#)]
27. Siliņa, L.; Dāboliņa, I.; Lapkovska, E. Sustainable textile industry—Wishful thinking or the new norm: A review. *J. Eng. Fiber. Fabr.* **2024**, *19*, 1–27. [[CrossRef](#)]
28. Harsanto, B.; Primiana, I.; Sarasi, V.; Satyakti, Y. Sustainability Innovation in the Textile Industry: A Systematic Review. *Sustainability* **2023**, *15*, 1549. [[CrossRef](#)]
29. De Ponte, C.; Liscio, M.C.; Sospiro, P. State of the art on the Nexus between sustainability, fashion industry and sustainable business model. *Sustain. Chem. Pharm.* **2023**, *32*, 100968. [[CrossRef](#)]
30. Abbate, S.; Centobelli, P.; Cerchione, R.; Nadeem, S.P.; Riccio, E. Sustainability trends and gaps in the textile, apparel and fashion industries. *Environ. Dev. Sustain.* **2024**, *26*, 2837–2864. [[CrossRef](#)]
31. Moran, C.A.; Eichelmann, E.; Buggy, C.J. The challenge of “Depeche Mode” in the fashion industry—Does the industry have the capacity to become sustainable through circular economic principles, a scoping review. *Sustain. Environ.* **2021**, *7*, 1975916. [[CrossRef](#)]
32. Luján-Ornelas, C.; Güereca, L.P.; Franco-García, M.-L.; Heldeweg, M. A Life Cycle Thinking Approach to Analyse Sustainability in the Textile Industry: A Literature Review. *Sustainability* **2020**, *12*, 10193. [[CrossRef](#)]
33. Moher, D.; Liberati, A.; Tetzlaff, J.; Altman, D.G.; The PRISMA Group. Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. *PLoS Med.* **2009**, *6*, e1000097. [[CrossRef](#)]
34. Rese, A.; Baier, D.; Rausch, T.M. Success factors in sustainable textile product innovation: An empirical investigation. *J. Clean. Prod.* **2022**, *331*, 129829. [[CrossRef](#)]
35. Dominidiato, M.; Guercini, S.; Milanese, M.; Tunisini, A. Supplier-customer relationships for sustainability-led innovation in the textile industry. *J. Bus. Ind. Mark.* **2023**, *39*, 15–26. [[CrossRef](#)]
36. Ruan, X.; Ding, N.; Yang, J. Dual-level eco-efficiency analysis in sustainable management: An empirical study on textile manufacturers and supply chains in China. *J. Environ. Manag.* **2022**, *304*, 114227. [[CrossRef](#)]
37. Siderius, T.; Poldner, K. Reconsidering the Circular Economy Rebound effect: Propositions from a case study of the Dutch Circular Textile Valley. *J. Clean. Prod.* **2021**, *293*, 125996. [[CrossRef](#)]
38. Pereira, F.; Carvalho, V.; Vasconcelos, R.; Soares, F. *A Review in the Use of Artificial Intelligence in Textile Industry*; Lecture Notes in Mechanical Engineering; Springer: Cham, Switzerland, 2022; pp. 377–392.
39. Ramos, L.; Rivas-Echeverría, F.; Pérez, A.G.; Casas, E. Artificial intelligence and sustainability in the fashion industry: A review from 2010 to 2022. *SN Appl. Sci.* **2023**, *5*, 387. [[CrossRef](#)]
40. Lee, W.; Sajadieh, S.M.M.; Choi, H.K.; Park, J.; Noh, S.D. Application of Reinforcement Learning to Dyeing Processes for Residual Dye Reduction. *Int. J. Precis. Eng. Manuf. Green Technol.* **2024**, *11*, 743–763. [[CrossRef](#)]
41. Ferlito, R. Industry 4.0 and sustainability: The case of the Italian textile district of Prato. *Compet. Rev.* **2024**, *34*, 995–1016. [[CrossRef](#)]
42. Sharma, A.; Singh, B.J. Evolution of modified LSS 4.0 model for sustainable Indian textile industry: A narrative review. *Int. J. Interact. Des. Manuf.* **2023**. [[CrossRef](#)]
43. Magri, M.; Ciarletta, P. Mathematics meets the fashion industry on path to product innovation and sustainability. *Proc. R. Soc. A Math. Phys. Eng. Sci.* **2023**, *479*. [[CrossRef](#)]
44. Kędzia, K.; Dziuba, R. A system for personalized clothing production as a model for supporting the competitiveness of SMEs on the example of Lodz Province. *Autex Res. J.* **2020**, *20*, 93–99. [[CrossRef](#)]
45. Petrillo, A.; Rehman, M.; Baffo, I. Digital and Sustainable Transition in Textile Industry through Internet of Things Technologies: A Pakistani Case Study. *Appl. Sci.* **2024**, *14*, 5380. [[CrossRef](#)]
46. Provin, A.P.; Regina de Aguiar Dutra, A.; Machado, M.M.; Vieira Cubas, A.L. New materials for clothing: Rethinking possibilities through a sustainability approach—A review. *J. Clean. Prod.* **2021**, *282*, 124444. [[CrossRef](#)]
47. D’Itria, E.; Colombi, C. Biobased Innovation as a Fashion and Textile Design Must: A European Perspective. *Sustainability* **2022**, *14*, 570. [[CrossRef](#)]
48. Bao, H.; Hong, Y.; Yan, T.; Xie, X.; Zeng, X. A systematic review of biodegradable materials in the textile and apparel industry. *J. Text. Inst.* **2024**, *115*, 1173–1192. [[CrossRef](#)]
49. Gupta, R.; Shukla, V.K.; Agarwal, P. Sustainable transformation in modest fashion through “RPET technology” and “Dry-uye” process, using recycled pet plastic. *Int. J. Recent Technol. Eng.* **2019**, *8*, 5415–5421.
50. Stenton, M.; Houghton, J.A.; Kapsali, V.; Blackburn, R.S. Review the potential for regenerated protein fibres within a circular economy: Lessons from the past can inform sustainable innovation in the textiles industry. *Sustainability* **2021**, *13*, 2328. [[CrossRef](#)]
51. Fu, C.; Wang, Z.; Gao, Y.; Zhao, J.; Liu, Y.; Zhou, X.; Qin, R.; Pang, Y.; Hu, B.; Zhang, Y.; et al. Sustainable polymer coating for stainproof fabrics. *Nat. Sustain.* **2023**, *6*, 984–994. [[CrossRef](#)]

52. Görse, E.; Mancar, M.; Ayvaz, N.; Durur, G. Ecological Approaches in Yarn Dyeing. *Advances in Science and Technology*. **2024**, *146*, 15–22.
53. Pizzicato, B.; Pacifico, S.; Cayuela, D.; Mijas, G.; Riba-Moliner, M. Advancements in Sustainable Natural Dyes for Textile Applications: A Review. *Molecules* **2023**, *28*, 5954. [[CrossRef](#)]
54. Rahaman, M.T.; Khan, M.S.H. Applications of green nano textile materials for environmental sustainability and functional performance: Past, present and future perspectives. *Nano-Struct. Nano-Objects* **2024**, *40*, 101332. [[CrossRef](#)]
55. Mikucioniene, D.; Mínguez-García, D.; Repon, M.R.; Milašius, R.; Priniotakis, G.; Chronis, I.; Kiskira, K.; Hogeboom, R.; Belda-Anaya, R.; Díaz-García, P. Understanding and addressing the water footprint in the textile sector: A review. *AUTEX Res. J.* **2024**, *24*, 20240004. [[CrossRef](#)]
56. Pundir, A.; Thakur, M.S.; Radha; Goel, B.; Prakash, S.; Kumari, N.; Sharma, N.; Parameswari, E.; Senapathy, M.; Kumar, S.; et al. Innovations in textile wastewater management: A review of zero liquid discharge technology. *Environ. Sci. Pollut. Res.* **2024**, *31*, 12597–12616. [[CrossRef](#)]
57. Holkar, C.R.; Jadhav, A.J.; Pinjari, D.V.; Mahamuni, N.M.; Pandit, A.B. A critical review on textile wastewater treatments: Possible approaches. *J. Environ. Manag.* **2016**, *182*, 351–366. [[CrossRef](#)]
58. Marovska, G.; Dushkova, M.; Angelova, G.; Brazkova, M.; Brink, H.; Haneklaus, N.; Menkov, N.; Slavov, A. Rose and lavender industrial by-products application for adsorption of Acid Orange 7 from aqueous solution. *Biomass Convers. Biorefinery* **2024**, *14*, 22703–22716.
59. Piribauer, B.; Bartl, A. Textile recycling processes, state of the art and current developments: A mini review. *Waste Manag. Res.* **2019**, *37*, 112–119. [[CrossRef](#)]
60. Kim, T.; Kim, D.; Park, Y. Recent progress in regenerated fibers for “green” textile products. *J. Clean. Prod.* **2022**, *376*, 134226. [[CrossRef](#)]
61. Bressanelli, G.; Visintin, F.; Sacconi, N. Circular Economy and the evolution of industrial districts: A supply chain perspective. *Int. J. Prod. Econ.* **2022**, *243*, 108348. [[CrossRef](#)]
62. Chand, S.; Chand, S.; Raula, B. Textile and apparel industries waste and its sustainable management approaches. *J. Mater. Cycles Waste Manag.* **2023**, *25*, 3132–3143. [[CrossRef](#)]
63. Kulkarni, M.B.; Gavande, V.; Mahanwar, P.A.; Shah, A.R.; Shuib, R.K.; Khare, A.M.; Radhakrishnan, S. Review on biomass sheep wool-based polymer composites. *Biomass Convers. Biorefinery* **2023**, *14*, 30961–30982. [[CrossRef](#)]
64. Battesini Teixeira, T.G.; de Medeiros, J.F.; Kolling, C.; Duarte Ribeiro, J.L.; Morea, D. Redesign in the textile industry: Proposal of a methodology for the insertion of circular thinking in product development processes. *J. Clean. Prod.* **2023**, *397*, 136588. [[CrossRef](#)]
65. Arnold, M.G.; Pfaff, C.; Pfaff, T. Circular Business Model Strategies Progressing Sustainability in the German Textile Manufacturing Industry. *Sustainability* **2023**, *15*, 4595. [[CrossRef](#)]
66. Ermini, C.; Visintin, F.; Boffelli, A. Understanding supply chain orchestration mechanisms to achieve sustainability-oriented innovation in the textile and fashion industry. *Sustain. Prod. Consum.* **2024**, *49*, 415–430. [[CrossRef](#)]
67. European Commission. Available online: <https://eippcb.jrc.ec.europa.eu/reference/textiles-industry> (accessed on 15 December 2024).
68. Cai, Y.J.; Choi, T.M. A United Nations’ Sustainable Development Goals perspective for sustainable textile and apparel supply chain management. *Transp. Res. Part E Logist. Transp. Rev.* **2020**, *141*, 102010. [[CrossRef](#)]
69. Thakker, A.M.; Sun, D. Sustainable Development Goals for Textiles and Fashion. *Environ. Sci. Pollut. Res.* **2023**, *30*, 101989–102009. [[CrossRef](#)]
70. Leal Filho, W.; Dinis, M.A.P.; Liakh, O.; Paço, A.; Dennis, K.; Shollo, F.; Sidsaph, H. Reducing the carbon footprint of the textile sector: An overview of impacts and solutions. *Text. Res. J.* **2024**, *94*, 1798–1814. [[CrossRef](#)]
71. Mehta, S. Biodegradable textile polymers: A review of current scenario and future opportunities. *Environ. Technol. Rev.* **2023**, *12*, 441–457. [[CrossRef](#)]
72. Yaqub, M.; Celebi, M.D.; Dilaver, M.; Bhagat, S.K.; Kobya, M.; Lee, W. Treating Textile Wastewater to Achieve Zero Liquid Discharge: A Comprehensive Techno-economic Analysis. *Water Air Soil Pollut.* **2023**, *234*, 651. [[CrossRef](#)]
73. Buljan, J.; Emmanuel, K.V.; Viswanathan, M.; Bosnić, M.; Král, I. Analysis of flow and energy aspects of Zero Liquid Discharge (ZLD) technology in treatment of tannery effluents in Tamil Nadu, India. In Proceedings of the 34th IULTCS Congress: Science and Technology for Sustainability of Leather Impact Factor, Chennai, India, 5–8 February 2017; pp. 244–259.
74. Jahan, N.; Tahmid, M.; Shoronika, A.Z.; Fariha, A.; Roy, H.; Pervez, M.N.; Cai, Y.; Naddeo, V.; Islam, M.S. A Comprehensive Review on the Sustainable Treatment of Textile Wastewater: Zero Liquid Discharge and Resource Recovery Perspectives. *Sustainability* **2022**, *14*, 15398. [[CrossRef](#)]
75. Masood, T.; Sonntag, P. Industry 4.0: Adoption challenges and benefits for SMEs. *Comput. Ind.* **2020**, *121*, 103261. [[CrossRef](#)]

76. de Vries, A. The growing energy footprint of artificial intelligence. *Joule* **2023**, *7*, 2191–2194. [[CrossRef](#)]
77. Yadav, V.S.; Majumdar, A. Mitigating the barriers of industrial symbiosis for waste management: An integrated decision-making framework for the textile and clothing industry. *Waste Manag. Res.* **2024**, *42*, 544–555. [[CrossRef](#)]

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