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Reciklaža i valorizacija tekstilnog otpada

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Apstrakt: Tekstilna industrija značajno doprinosi ekološkim izazovima , vođena prekomernom potrošnjom, brzom modom i oslanjanjem na neodržive materijale. Tekstil je četvrta roba koja ima uticaj na životnu sredinu, sa značajnim posledicama, uključujući iscrpljivanje resursa, emisije gasova staklene bašte i zagađenje, dodatno opterećeno dugim periodom raspada sintetičkih materijala i oslobađanjem mikroplastike. Napori za ublažavanje ovih pitanja uključuju propise EU koji promovišu recikliranje i principe cirkularne ekonomije. Metode reciklaže, kao što su: mehaničke, hemijske, biološke i hibridne, igraju ključnu ulogu u valorizovanju tekstilnog otpada u proizvode visoke vrednosti, kao što su geotekstili, kompoziti, izolacioni materijali i biogoriva. Ovi procesi, ne samo da smanjuju količine stvorenog otpada, već nude i ekološke prednosti, kao što su ušteda energije i smanjene emisije. Uprkos njihovom potencijalu, prepreke kao što su složena struktura otpada, neadekvatna infrastruktura, ekonomski izazovi i nedosledni propisi, ometaju široko usvajanje. Održiva tranzicija zahteva koordinisane napore u svim industrijama, kreatorima politike i potrošačima. Naglasak na inovacijama u tehnologijama recikliranja, biorazgradivim materijalima i energetski efikasnoj proizvodnji, može pojačati uticaj valorizovanih materijala, čineći kružne tekstilne sisteme izvodljivijim. Svest potrošača i odgovorna potrošnja dodatno jačaju ovu promenu . Rešavanje ovih izazova je od vitalnog značaja za smanjenje otpada, očuvanje resursa i unapređenje održive budućnosti za modnu i tekstilnu industriju.

Ključne reči: Tekstilni otpad, Reciklaža tekstila, tekstilne valorizacione tehnologije, Održiva praksa, Valorizovani materijali

Recycling and valorisation of textile waste

Abstract: The textile industry is a major contributor to environmental challenges, driven by overconsumption, fast fashion, and reliance on non-sustainable materials. Textiles are the fourth most environmentally impactful commodity, with significant consequences including resource depletion, greenhouse gas emissions, and pollution, worsened by synthetic materials' slow decomposition and microplastic release. Efforts to mitigate these issues include EU regulations promoting recycling and circular economy strategies. Recycling methods, such as: mechanical, chemical, biological, and hybrid, play a key role by valorizing textile waste into high-value products such as geotextiles, composites, insulation materials, and biofuels. These processes not only reduce waste but also offer environmental benefits like energy conservation and reduced emissions. Despite their potential, barriers such as waste complexity, inadequate infrastructure, economic challenges, and inconsistent regulations hinder widespread adoption. A sustainable transition requires coordinated efforts across industries, policymakers, and consumers. Emphasizing innovation in recycling technologies, biodegradable materials, and energy-efficient production can amplify the impact of valorized materials, making circular textile systems more feasible. Consumer awareness and responsible consumption further strengthen this shift. Addressing these challenges is vital for reducing waste, conserving resources, and advancing a sustainable future for the fashion and textile industry.

Keywords: Textile Waste, Textile Recycling, Textile ValorisationTechnology, Sustainable Practices, Valorised Materials

1. Introduction

Over the course of the last century, clothing has been elevated beyond its basic function, acquiring greater emotional, psychological, cultural and societal significance.

However, this shift in value, combined with the onset of the“Petrochemical Era” in the 1950s, has resulted in overconsumption of clothing, much of it composed of non-sustainable materials. Due to its association with fashion and economic status, the apparel industry has made a significant contribution to the volume and rate of waste generation (Navone et al., 2020).This includes the excessive use of finite fossil-based resources and energy. Textiles are the fourth most environmentally significant commodity globally, with textile waste i.e. the material discarded throughout the textile production process, causing considerable environmental, climate, and social impacts from a resource and waste perspective (European Environment Agency, 2024). According to the European Environment Agency (EEA) report, textiles accounted for 16.7 million tonnes of waste in 2018, making it the fourth largest waste stream in the EU by weight. The EEA predicts a 63% increase in clothing consumption, from 62 million tonnes in 2019 to 102 million tonnes in 2030 (Stefan et al., 2022). To limit the environmental impact of textile waste, the European Union has implemented several key regulations and directives aimed at promoting sustainability. The Waste Framework Directive (Directive 2008/98/EC, 2008) mandates that EU member states collect textiles separately by 2025, ensuring that materials are diverted from landfills and facilitating recycling and reuse. Additionally, the EU's Circular Economy Action Plan, part of the European Green Deal, outlines measures to reduce waste generation, improve resource efficiency, and promote circular strategies in various industries, including textiles. These initiatives are designed to reduce the environmental footprint of textiles throughout their lifecycle, from production to disposal, fostering a more sustainable and circular economy.

Textile waste includes a variety of materials such as fibres, fabrics, garments, and textile products that are no longer required for their original purpose and can occur at different stages of the textile supply chain. Based on composition, origin and characteristics, waste can be classified as natural fibres (cotton, wool, silk), synthetic fibres (polyester, nylon, acrylic), blended fibres, and textile products with complex structures or treatments like laminates, coated fabrics, and composite materials (Shirvanimoghaddam et al., 2020). The composition of textile waste produced globally in 2018 was estimated at 64% synthetic or originating from petrochemicals in general, and 36% natural fibres divided as follows: 24% cotton, 6% cellulosic, 1% wool and other natural fibres. Total weight was estimated at 105 million tonnes (Stone et al., 2020). Natural materials are more environmentally friendly than synthetic fibres, which are made from non-sustainable petrochemical-based products and require significant amounts of energy to produce (Payne, 2015). Therefore, managing the textile industry and its waste is crucial for reducing environmental impact, conserving resources, and promoting sustainable practices throughout the textile lifecycle (Bianco et al., 2023).

2. Recycling

Factors such as economic development, textile consumption patterns, and waste management infrastructure can influence waste generation rates and management practices. Common collection streams may include household or municipal solid waste collection, commercial or industrial collection, event-based collection initiatives, charitable organisations, textile collection bins, textile sorting facilities, textile recycling centers and landfill disposal. Landfill disposal is generally considered the least desirable option for textile waste management due to its negative impact on the environment, loss of resources, and contribution to landfill capacity issues (Mishra et al., 2022; Islam et al., 2019). However, in certain cases, landfill disposal may be necessary for certain types of textile waste that are not economically or technically feasible to recycle or recover. Effective collection streams and deposition methods for textile waste require coordination and collaboration among stakeholders, including waste management authorities, recycling companies, businesses, non-profit organisations, and consumers.

The most common methods for recycling textile waste include mechanical recycling, chemical recycling, upcycling, textile-to-textile recycling, energy recovery and hybrid recycling (Pensupaet al., 2017). Upcycling and textile-to-textile recycling involve repurposing and transforming the textile respectively, to new products of equal or higher value. Mechanical and chemical recycling break the textile down to fibres or its chemical constituents and reuses the recovered material, while hybrid recycling combines both methods. When textile waste cannot be recycled into new textile products, it can be used as a fuel source for energy recovery through incineration or combustion processes. Biological recycling is also a method that is gaining attention recently, as it is a sustainable solution depending on biotechnology, that could play a transformative role in textile waste management, especially for blended fabrics, natural fibers, and low-energy systems. Further categorization of the technologies employed can be seen in Table 1.

Innovative approaches are employed to develop a more sustainable, cheap and efficient process to address textile waste in the fashion and textile industries. Converting waste into value-added products is essential to reducing environmental pollution and thereby achieving a circular economy through proper waste management practices (Singhal et al., 2023; Lu et al., 2022; Mishra et al., 2022).

Table 1. Further categorization of the technologies used in the different recycling categories. Hybrid recycling is not shown, as it combines methods from the categories presented.

Mechanical Recycling	Chemical Recycling	Upcycling, Textile – to Textile	Biological Recycling	Energy Recovery
Shredding / Garnetting	Depolymer-ization	Creative Upcycling	Enzyme Treatment	Thermal Gasification / Pyrolysis
Needle - Punching	Cellulose Recovery	Fiber – to Fiber Regeneration	Fungal Degradation	Refuse – Derived Fuel
	Solvent – Based Processes		Bacterial Degradation	

3. Life Cycle Assessment and Valorisation

The environmental impact of a product from its production until its elimination (cradle to grave) is evaluated in a Life cycle assessment (LCA). A comprehensive LCA can be complex due to the variety of materials and methods involved in the manufacturing and recycling processes. Regarding textile waste recycling and valorisation, key aspects that are evaluated in LCA are the recycling technologies mentioned above, in comparison to virgin textile production. Mechanical recycling is assessed to have reduced energy consumption compared to virgin textile production. Chemical recycling can potentially lower the emissions generated through the process, while upcycling and donation extends the lifecycle of textiles, reducing the need for new materials and the volume of textile waste produced.

Finally, incineration of textile waste can provide energy recovery in comparison to landfill disposal.Valorisation of textile waste involves finding innovative ways to repurpose textile waste into valuable products and may include fibre recycling, combined with the recycling technologies mentioned above, or upcycling techniques such as cutting, stitching, quilting, and embellishing pieces of textile into new products with added value.This exploitation not only facilitates the environmental benefits mentioned above, but also has social benefits, by creating economic opportunities and support local communities through job creation, skills training, and social inclusion programs, particularly in regions with strong textile manufacturing traditions.

Table 2. Products originating from textile waste.

Waste Used	**Method**	**Product**	**Reference**
Synthetic	Mechanical (Needle -punching)	Geotextiles	Leon et al. 2016
Blended	Mechanical (Shredding)	Textile fiber – reinforced composites for insulation, acoustic panels, or construction materials	Echeverria et al. 2019, Hassanin et al. 2018, Jin et al. 2025
Leather	Mechanical (Shredding, Mixing)	Leather-rubber composites for use in apparel and shoes	Barrera Torres et al. 2025
Sludge	Hybrid	No-slumpconcretemixtures	Fernandes et al. 2025
Blended (Polyester – Cotton)	Hybrid	Antibacterial and UV protected textiles	Darwesh et al. 2024

Salt-rich Wastewater	Chemical	Skin/hide preservation in the leather industry	Ramesh et al. 2024
Blended (Cotton-Spandex)	Chemical (Solvent – Based Processes)	UV-blocking cellulose/graphene films and transparent polyurethane (PU) film	Xia et al. 2025
Natural	Biological (Biodegradation)	Compost, soil enrichment	Subramanian et al. 2020, Selvam et al. 2019
Wastewater	Biological (Bacterial Degradation)	Treatedwater for irrigation	Sen et al. 2019, Pazdzior et al. 2019
Blended	Biological (Fungal Degradation)	Synthetic fibers for re-processing and re-use, increased landfill space	Freemanetal. 2024
Blended	Biological (Fungal Degradation / Bioremediation)	TW was used as substrate for edible fungi cultivation	Hazelgrove&Moody, 2024
Synthetic (Viscoze)	Carbonization	Absorbents of pesticides in water	Tasić et al. 2025
Sludge and Tannery Fleshing	Energy Recovery (Co-hydrous Pyrolysis)	Energy recovery (biocrude, biochar, syngas)	Hossain et al. 2024

Table 2., shows several examples of products manufactured from textile waste, while Table 3., shows resources recovered from it with potential to use in products.

Table 3. Raw materials originating from textile waste

TW Used	**Method**	**Derived Material**	**References**
Blended	Mechanical	Raw materials for spinning into yarns and fabrics	Raiskio et al. 2025
Blended	Hybrid (Shredding, Calcination, Hydrothermal)	δ-MnO_2/C photothermal catalyst with high activity to remove indoor CH_2O	Wang et al. 2025
Synthetic (Polyester)	Hybrid (Milling, Enzymatic Hydrolysis)	PET of reduced crystallinity, terephthalic acid (TPA) for industrial applications	Zhou et al. 2025
Cellulose-rich	Chemical(CatalyticHydrothermalConversion)	Levulinic acid (solvents, fuel and oil additives, plasticizers, and pharmaceuticals)	Ozsel 2021
Cellulose-rich	Chemical (HydrothermalHydrolysis)	Hydrogengas	Ozsel 2021
Synthetic (Coloured Polyester)	Chemical (Aminolysis/ Glycolysis)	bis(2-hydroxyethyl) terephthalamide (BHETA) and bis(2-hydroxyethyl) terephthalate (BHET)	Anbarasu et al. 2024
Synthetic	Chemical (Ionic Liquid-assisted Regeneration)	Transparent renewable jute film (degradable packaging, electrically conductive films)	Zhong et al. 2021

Blended (PET and Wool)	Biological (Enzymatic Hydrolysis)	Pure polyester fibers and amino acids (feedstock material)	Mihalyi et al. 2025, Boschmeier et al. 2024
Blended Synthetic (Viscose and Polyamide)	Biological(EnzymaticHydrolysis)	Polyamide fibers, Polyhydroxybutyrate (PHB) and Bacterial cellulose (BC) (Glucose utilisation)	Mihalyi et al. 2024
Synthetic (Viscose)	Biological(EnzymaticHydrolysis)	D - Lactic acid (Glucose utilisation)	Campos et al. 2024
Non-recyclable	Energy Recovery (Pyrolysis / Gasification / Anaerobic Degradation)	Biofuel (biogas, biodiesel, ethanol, biochar)	Juanga-Labayen et al. 2022, Wojnowska-Baryła et al. 2022, Serrano et al., 2025
NaturalFiber	Energy Recovery (EnzymaticHydrolysis)	Succinic acid (feedstock material, food additive)	Li et al. 2019
Synthetic	Energy Recovery (Catalytic Pyrolysis)	Syngas and CH_4	Kwon et al. 2021

4. Challenges

The valorisation of textile waste presents a promising opportunity to reduce environmental pollution and foster a circular economy. However, several challenges impede the widespread adoption of these practices. One key challenge is the complexity of textile waste streams, which are composed of various materials, fibres, dyes, finishes, and contaminants, making them difficult to sort and process efficiently (Mishra et al., 2022). The diverse nature of textile waste requires specialised handling techniques for different materials, further complicating recycling efforts. Additionally, many regions suffer from a lack of proper infrastructure for waste collection, sorting, and recycling, limiting the capacity to process textile waste and often resulting in reliance on landfills or incineration (Stefan et al., 2021).

Economic viability is another significant hurdle to the effective valorisation of textile waste. The cost of collecting, sorting, and processing waste can often outweigh the value of the recycled materials, making the economic feasibility of textile recycling challenging (Mishra et al., 2022). This issue is compounded by the low consumer demand for recycled textile products and limited awareness of the environmental benefits of sustainable alternatives. Moreover, textile waste is often contaminated with dirt, oil, chemicals, and other impurities, which can degrade the quality of recycled materials, necessitating additional processing steps or purification to meet market standards (Kim et al., 2021). Furthermore, although promising, current recycling technologies such as fibre-to-fibre and chemical recycling remain in the early stages of development, and their scalability and cost-effectiveness need further improvement (Stanescu et al., 2021).

Finally, regulatory and policy barriers are a significant obstacle to the growth of textile waste valorisation efforts. Inconsistent regulations and a lack of supportive policies across regions hinder investment and innovation in the recycling sector (Pensupa et al., 2017). The absence of extended producer responsibility (EPR) schemes and clear waste management regulations impedes the adoption of circular economy principles within the textile industry. Additionally, the culture of fast fashion, characterised by low-cost, disposable clothing, continues to contribute significantly to textile waste generation, complicating efforts to reduce waste and promote recycling (Stanescu et al., 2021).

To overcome these challenges, collaboration among stakeholders, investment in research and development, and the implementation of supportive policies are crucial steps in advancing textile waste valorisation and enabling the transition to a circular economy.

5. Environmental sustainability

The production of synthetic polymers has significant negative environmental impacts. These materials contribute to pollution through the emission of greenhouse gases, the creation of microplastics, and the release of toxic chemicals such as dyes and chemical reagents. Similarly, the production of natural polymers, such as cellulose and protein fibres, used in clothing manufacture can harm the environment. Soil pollution results from the use of pesticides and fertilisers, while large volumes of water are consumed for irrigation in the production of natural fibre-based clothing (Stefan et al., 2022).

To mitigate these issues, it is crucial to identify hotspots within the life cycle of textile products where targeted actions can reduce their overall environmental impact. A cradle-to-grave analysis of textile products, considering type, composition and intended use, can provide valuable insights.

While significant attention has been given to the production and disposal phases, the distribution and consumption phases remain underexplored. Emerging consumption patterns, such as sharing and renting platforms, highlight the need for comprehensive data collection to assess their environmental performance.

Although circular practices have shown potential environmental benefits, further research is required to evaluate potential impact shifts between different life cycle phases. Additionally, there is a notable lack of studies comparing fibre types, ownership models, manufacturing processes, and disposal methods for the same functional unit. Such data would be essential for designing low-impact textile products. Despite growing awareness, the environmental implications of these factors remain under-researched among academics and practitioners in the textile industry (Amicarelli et al., 2022). Nevertheless, current evidence suggests that the production and use phases are the primary contributors to negative environmental impacts, whereas the end-of-life phase generally has a minor impact (Stanescu et al., 2021).

The environmental sustainability of textile waste valorisation depends on the adoption of environmentally friendly technologies, the implementation of sustainable waste management practices, and the integration of circular economy principles into textile production and consumption processes. Key considerations for improving sustainability include resource conservation, waste reduction, energy and emissions reduction, water conservation, and pollution prevention. By prioritising efficiency and adopting a life cycle approach, stakeholders can enhance the environmental sustainability of textile waste valorisation initiatives and contribute to a more sustainable and circular textile industry.

6. Fashion industry

The global fashion industry, currently valued at over $1.5 trillion, is as destructive as it is lucrative, leaving behind vast amounts of textile waste. Up to 80 billion new garments are produced annually, and as much as 92 million tonnes of clothing end up in landfills each year, most of itderiving from synthetic materials (Chen et al., 2021).This waste is driven by the rise of fast fashion, characterised by its rapid production cycles and disposable nature. The fast fashion industry can have significant environmental impacts, such as increased greenhouse gas emissions, water usage, and waste generation. Additionally, the low prices associated with fast fashion brands can lead to exploitative labour practices in garment factories.

The environmental consequences of synthetic textiles are staggering. Each wash of synthetic garments releases tiny plastic microfibres into waterways, contributing up to 500,000 tonnes of microfibres to the ocean every year (Boucher & Friot, 2017).

Consumers play a pivotal role in driving fast fashion. Demand for cheap clothing has led to global clothing production doubling between 2000 and 2015. On average, each individual uses 11.4 kilograms of clothing annually, producing the equivalent of 442 kilograms of CO_2 emissions per capita (Svensson, 2020). Today's consumption patterns are unsustainable: people buy 60% more clothing than they did 15 years ago yet wear each item 50% less frequently. At this rate, global clothing sales are projected to reach 160 million tonnes by 2050 (Andreadakis& Owusu – Wiredu, 2023).

Despite the daunting statistics, solutions exist to mitigate the environmental impact of fashion waste. As consumers, our purchasing habits directly influence the industry, and by adopting sustainable practices, we can drive the transition towards a circular and eco-friendly fashion system. Many brands are also innovating with recycled materials, creating clothing from post-consumer textile waste, discarded plastic bottles, or nylon fishing nets (Leonas, 2017). Supporting brands that specialise in upcycled garments or use organic fibres, which are biodegradable and require fewer resources to produce, fosters sustainable practices within the industry.

Additionally, the fashion industry is increasingly adopting environmentally friendly production methods, such as waterless dyeing techniques, carbon-neutral factories powered by renewable energy, and efficient waste-reduction practices (Mahmud & Kaiser, 2020; Xu et al., 2023), all of which help reduce the environmental footprint of textile manufacturing. Ultimately, raising awareness of the environmental impacts of fashion can inspire change, and by prioritising lifecycle thinking and making mindful choices, consumers can encourage the industry to adopt more sustainable practices.

The transition to a sustainable textile industry requires collective action from consumers, brands, and policymakers. Through resource conservation, waste reduction, and innovative production methods, we can reduce the environmental burden of fashion waste and pave the way for a more circular and sustainable future.

7. Conclusions

The production of textiles demands significant resources, including water, energy, and raw materials, which are often wasted when clothing is discarded instead of being reused or recycled. Discarded textiles take up considerable space in landfills and contribute to greenhouse gas emissions as they decompose. Many of today's textiles are made from synthetic fibres that can take hundreds of years to break down, releasing harmful chemicals into the environment during this process. The increase in textile consumption has led to a corresponding rise in post-consumer waste, exacerbating environmental challenges. The fast fashion cycle, characterised by cheaper textiles with shorter lifespans, has significantly contributed to the growing issue of textile waste. To address this, a shift towards upcycling textile waste has emerged, helping to recover materials and energy consumed during production and reducing the carbon and water footprints of these products. The transition from a linear economy, which dominates the textile industry, to a circular economy has become essential, driven by the scarcity of raw materials and fossil fuels, as well as the severe environmental impacts of waste disposal. As the fashion industry is responsible for a significant amount of waste and pollution, there are now more responsible options for consumers to make choices that align with environmental sustainability. By choosing sustainable brands and adopting more mindful purchasing practices, individuals can contribute to reducing the fashion industry's environmental footprint. Ultimately, the valorisation of textile waste offers substantial environmental benefits, including resource conservation, waste reduction, and the promotion of social opportunities through job creation and community support. While challenges remain in areas such as bioremediation and textile effluent treatment, innovations in technologies like enzymatic hydrolysis and membrane bioreactors show promise in improving textile waste management. By adopting comprehensive waste management strategies, encouraging recycling and reuse initiatives, and raising awareness about the need for change, we can collectively mitigate the environmental impact of textile waste and work towards a more sustainable approach to textile consumption and disposal.

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