Innovations and Opportunities in Sustainable Textile Recycling

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Abstract. Waste or wastage is the term for materials that remain unutilized after a product's initial use or process completion. It is a type of substance that is worthless, ineffective, or flawed. Thus, material that loses its value or becomes unusable after the creation of any textile product has concluded is referred to as textile waste. Produce waste occurs during all phases of the textile production process, including spinning, weaving, knitting, dying, finishing, and garment making. This study examines the effects textile waste on the environment and the difficulties in recycling procedures within the industry, which is crucial for the world economy and ecosystem. It is crucial to move towards a circular economy model since the textile industry produces a lot of trash because of its fast fashion cycles and high levels of production to meet demand. This study emphasizes the textile industry's significant environmental impact. The conclusions show that although textile recycling can help lessen the industry's environmental impact, there are still a number of obstacles to overcome, including the need for low-grade materials to have commercially viable recycling processes, the high cost of recovery procedures, and the logistical and technical challenges associated with separating fiber blends. In order to deal with these issues, the study emphasizes how crucial it is to develop environmentally friendly procedures and cutting-edge recycling technologies.

Keyword-: Waste Management, Textile Waste, Environmental impact, recycling, Challenges.

1 Introduction

As a result of the worldwide energy crisis as well as the contamination of the environment, everyone truly require transportable outstanding durability energy-storage systems [1-2]. Scholars have been drawn to super capacitors amongst energy-storage systems as a result of its exceptional qualities, which include a substantial power density, quick charging and discharging, extended cycle stable lifespan, security, and ecological sustainability. The textile sector stands as one of the most substantial and historical industries globally, boasting a market value of around USD 1.3 trillion and providing jobs for over 300 million individuals throughout its entire value chain [3-6]. Despite its economic significance, the industry is also known for its extensive environmental impact, spanning from the initial stages of textile production to the disposal of end-of-life products, presenting significant challenges in terms of resource use and environmental degradation [7]. Notably, the textile industry ranks as the second-largest source of water and carbon footprint, trailing only behind oil and gas exploration and is responsible for 10% of worldwide carbon emissions. This considerable environmental toll is due to the vast quantities of textile goods manufactured to meet the needs of an expanding global population, improved living standards, and rising worldwide incomes [8].
The fast evolution of fashion developments has caused an uptick in each fabric manufacturing and the generation of waste. The environmental effects of producing, the use of, and casting off textiles are nicely-installed. In response, the textile enterprise is moving away from the traditional linear economic system model of "take-make-waste" towards embracing the concepts of a round economy. This shift aims to reintegrate textiles into the product lifecycle, stopping waste and developing a sustainable loop that conserves sources and minimizes environmental damage, as shown in Fig. 1. Thus, the technique of valorizing fabric enterprise waste to reclaim fibers and create high-fee products has attracted growing hobby. The valorization manner of textile waste encompasses three number one phases: pretreatment, enzymatic hydrolysis, and the regeneration of fibers [9].

Fig. 1: Potential applications of recycled fibers derived from textile waste [9]

A large environmental difficulty is the pollutants as a result of the accumulation of used apparel in municipal solid waste (MSW) landfills, discarded by way of each customers and the style industry. US environmental protection corporation (USEPA) reported in 2018 that fabric waste constituted 5.8% of the whole MSW in landfills, amounting to approximately 17 million heaps. The environmental challenges posed through the developing pile of non-biodegradable textile waste, coupled with the decreasing availability of landfill areas, have brought on the textile and fashion sectors to don't forget and enforce environmental friendly strategies at some stage in the lifecycle of textile products [10]. This urgent need to reduce the amount of textile waste ending up in landfills has driven researchers to explore innovative and sustainable methods for including value and locating useful makes use of for these materials. Mitigating the environmental effect of textile waste calls for the development of recent technology and procedures for its recuperation, recycling, and reuse, aiming to reclaim its economic price and provide feasible landfill options. Adopting the principles of a circular or closed-loop textile financial system presents a sustainable solution, contrasting the traditional open-loop device of fabric waste control [11].

The surge fashion textile consumption leads to an increasing volume of waste. Ideally, given that nearly all fashion textiles are recyclable, there should be no waste in the textile and apparel sector. Additionally, according to Fig. 2, it's estimated that over 60% of all recovered garments could be repurposed, 35% could be transformed into cleaning cloths and for fiber recycling purposes, leaving only 5% that would actually need to be disposed of. Despite these possibilities, a large portion of textile waste ends up in landfills in practice. This highlights the importance of understanding the challenges encountered by leading economies in managing textile production and waste. The key economies analyzed in this context include China, the European Union, the United States, and Canada [12].

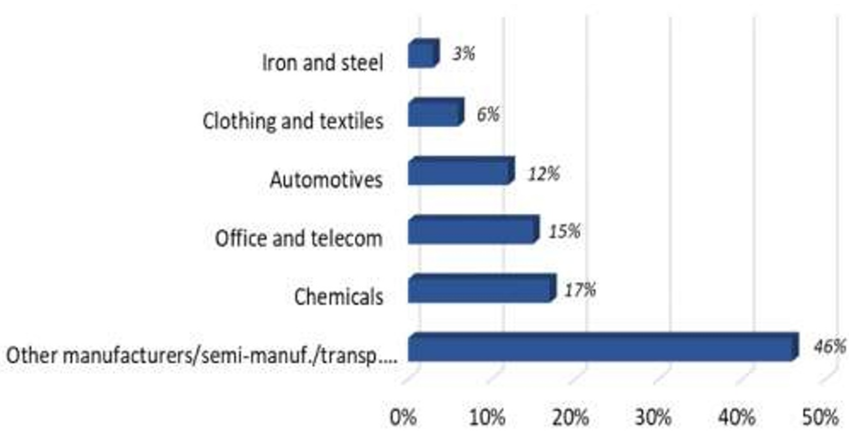

Fig. 2: Share of global exports of manufacture products in 2017 [12]

The bar graph given in Fig. 2 shows that the clothing and textiles sector, accounting for 6% of the total, has a smaller impact than other industries. This could be due to factors like waste generation or recycling, with only a small portion of materials coming from recycled clothing and textiles. The graph suggests room for improvement in terms of increasing its share of the category, potentially benefiting from positive contributions like recycling rates or indicating the need for targeted waste reduction strategies [13].

2 Environmental Impact of Textile Waste

Worldwide, approximately 87% of disposed textiles find their way into landfills, with over 90% of these materials being recyclable or reusable. Fig. 3 shows the transformation of textile waste into cost-added products isn't simplest environmentally beneficial but also economically feasible. Information of the environmental advantages and impacts associated with diverse recycling approaches is vital for incorporating recycling practices into the clothing waste management method [14]. With the growing call for fabrics, issues concerning the environmental consequences of fiber manufacturing and next disposal approaches have grown to be greater stated [15]. The ultimate goal of one of the performed study at is to create a sustainable environment through developing brick via the combination of commercial waste from the steel zone. One of the main wastes created during the manufacture of aluminium alloys is aluminium dross.

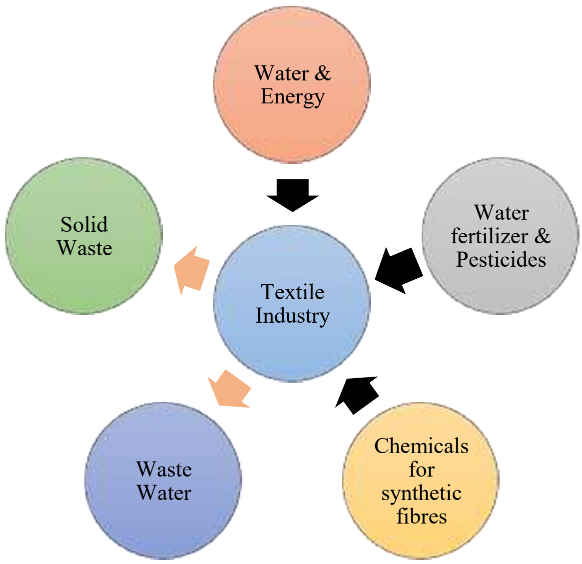

Fig. 3: Environmental impact factors of the textile industry

2.1 Contribution to Landfills

Nowadays, the issue of textile waste disposal has garnered elevated attention worldwide. Market expansion inside the fabric enterprise is influenced now not most effective by using populace increases but also by means of financial shifts and developments in style [16]. The rapid turnover within the fast fashion industry has resulted in heightened ranges of intake and corresponding waste. This fashion is regarding due to the significant environmental pollutants related to the textile and garment sector, one of the main polluting industries. Textile production is closely reliant on chemicals and consumes massive quantities of water, leading to massive wastewater and fiber waste. While fiber waste largely originates from surplus or discarded clothing within the supply chain, it encompasses a variety of materials such as natural fibers, synthetic fibers, and their blends [17]. Notably, natural fibers, primarily composed of cellulosic materials, present an opportunity for repurposing into bio-based products. Despite the significant role of developing countries in the textile industry, there's a lack of data on their textile waste management practices and the resulting environmental impacts. The study conducted in [18] examined two hazardous solid waste treatment methods for acrylic fibers: landfill and incineration. The findings showed that incineration is the more environmentally friendly option, with lower impacts on human health (28% compared to landfill's 46.8%) and a somewhat higher impact on ecosystem quality than landfill. Incineration also had a higher impact on resources. However, both impacts could be lessened through the use of advanced landfill or incinerator technology and by adopting waste-to-energy methods. The annual generation of post-consumer textile waste (PCTW) in the U.S. has escalated to over 34 billion pounds, with 66% going to landfills, 19% incinerated for energy, and only 15% recycled. A study conducted in [19] using data from Florida revealed that higher-income, racially segregated areas with more clothing stores generate more PCTW, while landfills are more prevalent in lower-income areas. Recycling rates were similar across counties. The findings suggest an environmental justice issue where wealthier areas contribute more to textile waste, which disproportionately affects poorer communities with more landfills.

2.2 Greenhouse Gas Emissions

In China, the textile industry is the sixth largest in energy consumption and is striving to decrease its greenhouse gas (GHG) emissions. The study provided in [20] undertakes a detailed examination of GHG emissions, finding that coal is the predominant source, contributing most to the industry's emissions, followed by electricity mainly sourced from the Eastern, Central, and Northern China Power Grids. Through a driving force factor analysis, it was determined that production scale significantly increases GHG emissions, whereas reductions in energy intensity and optimization of energy structure can mitigate them. The study identifies that interventions in spinning, weaving, and wet processes hold substantial energy-saving potential, offering a short payback period. Under an optimal technology scenario, GHG emissions could be reduced by 34.3% compared to the baseline in 2030, with emissions per unit output value potentially reaching 0.18 t/million RMB, close to the advanced international benchmark of 0.14 t/million RMB. The Ellen MacArthur Foundation highlights that 73% of used clothing ends up in landfills or is incinerated, and fabric production in 2015 resulted in 1.2 billion tons of GHG emissions. The study conducted in [21] focused on Japan, where no prior research quantified GHG savings from clothing reuse and recycling. It estimated Japan's GHG emission reduction from processing 6.03 × 108 kg of used clothing through various methods at approximately 6.60 × 109 kg CO2e. Overseas reuse accounted for 60% of this reduction. This effort in Japan corresponds to a 70% reduction in GHG emissions compared to incinerating all household waste.

2.3 Water and Soil Pollution

A field experiment with Noor Fatima Fabrics Private Ltd. in Faisalabad tested the impact of using wastewater from the textile industry's bleaching, printing, and end drain units on wheat growth in saline sodic soil, compared with canal water. Applying liquid NPK fertilizer with end drain wastewater significantly improved various growth metrics and yields of wheat by up to 21-44% over the control (canal water). NPK uptake in grains also rose by 15-30%, and heavy metal concentrations in grains decreased [22]. Untreated effluents from textile mills pose significant risks to ecosystems and human health due to their content of dyes, metal pollutants, and various organic compounds used in processes like softening, printing, and heat stabilization. When these complex effluents are released into the environment without adequate treatment, they can contaminate natural water sources and soil. Soil, a crucial layer on the Earth's surface, provides plants with anchorage and holds water and nutrients. However, the presence of xenobiotic substances from industrial or domestic waste in open or inadequately sealed pits can change the soil's chemical and physical characteristics, impacting its fertility [23]. The study conducted in [24] explored the impact of textile wastewater on soil and Lycopersicon esculentum (tomato) plants, using wastewater concentrations of 0, 20, 40, 60, and 80%. At 80% concentration, significant reductions were observed: chlorophyll content dropped by 62.5%, protein and nitrogen content by 71.29% and 71.65%, respectively, and growth parameters such as root length (61.9%), shoot length (70.8%), root dry weight (69.2%), shoot dry weight (70.5%), and total dry weight (67.3%) decreased. Soil metal content increased, with copper (Cu) levels at 0.725 to 1.89 gm kg^{-1} and chromium (Cr) at 6.54 to 8.40 gm kg^{-1} across pre-flowering, peak flowering, and post-flowering stages, indicating a correlation between wastewater concentration and heavy metal accumulation. Table 1 synthesizes key findings from recent studies that highlight the scale of environmental impacts associated with textile waste management, GHG emissions, and pollution. It also outlines the numerical values quantifying these impacts and proposes mitigation strategies to address them.

Table 1: Environmental challenges and mitigation strategies in the textile industry: comparative analysis

Reference	Key Findings & Numerical Values	Environmental Impact	Mitigation Strategies
[8]	Incineration vs. landfill for acrylic fibers: Incineration has lower human health impacts (28%) compared to landfill (46.8%), but higher ecosystem quality impact.	Incineration reduces human health risks but increases ecosystem impact.	Advanced landfill/incinerator technology and waste-to-energy methods can lessen impacts.
[9]	U.S. PCTW: Over 34 billion pounds annually, with 66% landfilled, 19% incinerated for energy, and only 15% recycled. Higher-income areas generate more PCTW, affecting poorer communities with landfills.	Highlights environmental justice issues with textile waste disproportionately affecting poorer communities.	Improved recycling methods and equitable waste management practices are needed.
[10]	China's textile industry GHG emissions: Coal is the main source. Production scale upsurges emissions, whereas energy intensity reductions and energy structure optimizations can mitigate them. Potential 34.3% GHG reduction by 2030.	Coal dependency significantly contributes to GHG emissions.	Implementing energy-saving technologies in spinning, weaving, and wet processes can substantially reduce GHG emissions.
[11]	Japan's GHG emission reduction from used clothing processing estimated at ~6.60 × 10⁹ kg CO2e, with 60% reduction from overseas reuse.	Reuse of clothing can lead to a significant reduction in GHG emissions.	Promoting clothing reuse and recycling can contribute to a substantial decrease in GHG emissions.
[12]	Wastewater from textile industry used on wheat in saline sodic soil	Wastewater reuse in agriculture shows potential	Liquid NPK fertilizer combined with textile

	increased yield by 21-44% over control, NPK uptake by 15-30%, and decreased heavy metal concentrations in grains.	benefits but requires careful management of contaminants.	wastewater can be beneficial for agriculture if contaminants are managed.
[14]	Textile wastewater impact on tomato plants: 80% concentration reduced chlorophyll by 62.5%, protein and nitrogen by 71.29% and 71.65%, and growth parameters significantly. Soil metal content increased with wastewater concentration.	Textile wastewater significantly harms plant health and soil quality, indicating a need for effective wastewater management.	Adequate treatment of textile effluents is crucial to prevent soil and water pollution and protect ecosystem health.

The textile industry stands as one of the most significant contributors to environmental degradation, prompting an urgent call for sustainable practices and innovative solutions. This sector's impact spans various dimensions, including landfill contribution, greenhouse gas (GHG) emissions, and water and soil pollution. The urgency to address these challenges is compounded by the industry's rapid growth, fueled by fast fashion and global demand increases. By comparing different aspects of the industry's environmental footprint, the table aims to shed light on the critical areas where interventions are needed and suggests pathways towards more sustainable textile production and waste management practices.

3. Textile Recycling

The potential of transforming textile waste into valuable resources through recycling and sustainable practices is significant, yet its realization on a large scale faces substantial challenges. One of the primary obstacles is the need to minimize the mixing of different fibres. Fig. 4 shows the technique of recycling textiles waste, in order to utilize them in sustainable way. This step is crucial because separating blends post-consumption is both costly and complex, hindering the feasibility of fibre-to-fibre recycling, especially for new fabrics made from blended textiles [25]. The barriers to effective recycling are multifaceted. As infered from the studies it has been found that there is a noteworthy absence of commercially feasible technologies for recycling low-grade textile materials, which is mainly because the developed, large-scale processes for separating fibres in mixed and composite textiles [26–28] are not available inf abundance. It can also be found that, the high costs incurred by textile recovery method are present when combined with the presence of low-quality materials and mixes in the recycling market, that finally leave a considerable impact on the quality of the final product [29]. The local and reginal scale of recycling suffer beacuse the logistics of recycling are not only costly but also complicated [30].

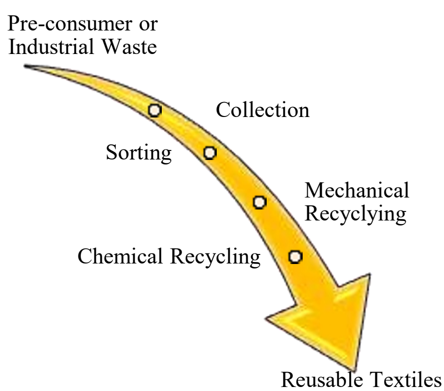

Fig. 4: Technique of recycling textiles

LCAs are essential tools for assessing the environmental sustainability of textile recycling techniques. They contain an extensive evaluation of the mechanical or chemical tactics used to break down fabric waste into reusable fibers or materials, making sure they may be efficient and minimally harm the environment [31,32]. The LCA approach additionally includes an intensive investigation of the logistics involved in textile recycling, considering the distances recycled substances journey from collection to recycling facilities and again to purchasers as new merchandise. The energy is utilised in to process materials and then make its transportation and hence it forms an important aspect of LCAs. Any subjected methodoogy when fails to pass on the LCA test, it could end up being as not ecologically friendly as anticipated, and therefore causing more harm than benefit. Therefore, it can be found that LCAs are critical for guiding innovators towards solutions that reduce severe environmental impacts while recognising areas that are in need of reengineering or replacement with healthier options.

5 Conclusion

A massive amount of fabric waste is burned or disposed of in landfills, which releases greenhouse gases into the atmosphere and contaminates water and soil. The look at highlights the significance of transferring closer to a round financial system by using displaying how recycling and reusing textile waste can greatly lessen those effects. To allow green recycling at scale, the observation in this study also identifies vast boundaries within the field of textile recycling, along with logistical, financial, and technological ones.

a. Massive fabric waste releases greenhouse gases and contaminants. Recycling and reusing textile waste can reduce these effects.
b. The study identifies logistical, financial, and technological barriers in textile recycling. Lifestyles Cycle assessments (LCAs) are crucial for sustainability assessment.
c. Coordinated efforts with clients, industry stakeholders, and legislators are needed for a sustainable fabric industry.
d. Successful steps can significantly benefit the environment, supporting the industry's environmental efforts and achieving global sustainability targets.

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