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Fashion's environmental toll: Textile waste and the urgency for sustainable solutions

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Abstract

The world is on the verge of an impending crisis of textile waste, brought about as a result of the combined effects of a rising global population, burgeoning living standards and the shorter lifecycle of textile products. Textile recycling is the answer to help combat the enormous amount of waste created by the fashion and textile industries. While this is crucial to the growth of the textile waste recycling industry, practical and actionable interim solutions are still necessary. Textile waste is a significant stain on human life from both economic and environmental perspectives. From raw materials to finished products, clothing production from natural or synthetic sources can play a role in pollution and waste generation. This review article analyzes the economic and environmental implications of the fashion and textile industries. It assesses these waste recovery technologies and techniques, as well as the recycling at various stages of production and the use of the resulting recycled products. The recycling processes for textile waste have made some notable advances; however, some gaps remain unaddressed. Challenges include multi-scaler industrialization, waste treatment and separation processes, as well as waste contamination, such as mixed chemicals. And greater awareness is needed among consumers of the value of fiber-to-fiber recycling, as technological progress in this field has not matched its need. On the whole, this article is a good resource to gain a sense of the current landscape of recycling and recovery in textiles, clothing, and fashion.

Keywords: Textile recycling; Textile recovery; Textile waste; Fast fashion; Garment industry; Sustainability

1. Introduction

The combination of global population growth, improved living conditions, overproduction, lower prices, and the shortened lifecycle of textile products has led to a significant textile waste crisis in recent years. Textiles are used in various sectors, including clothing (such as casual wear and uniforms), home furnishings (like curtains, bedding, and tablecloths), industrial applications (such as filtration systems and conveyor belts), medical fields (including surgical waste and wound dressings), and sportswear. [1-5]

The fashion and apparel industries play a major role in exacerbating this crisis. A large number of people worldwide have adopted the "fast fashion" trend, leading them to purchase cheaper garments produced in vast quantities in response to the latest trends. Due to frequent stock turnover, this practice has become a serious environmental threat. The fashion industry is responsible for approximately 4–5 billion tons of carbon dioxide emissions annually, accounting for around 10–12% of total global emissions. Additionally, it is one of the largest consumers and polluters of water, using approximately 79 billion liters of water per year. Around 20% of industrial water pollution is linked to textile dyeing and finishing processes. [6-12]

Despite efforts toward sustainability in recent decades, the industry still requires fundamental changes in production and consumption methods. Adjusting usage patterns in the textile sector and implementing long-term strategic plans

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by international organizations are essential for changing consumer behavior and minimizing financial and environmental losses. To promote sustainability, consumers may need to reduce the frequency of purchasing new clothing and extend the lifespan of their garments. Given the finite availability of natural resources, it is crucial to manage them efficiently by reducing reliance on virgin raw materials through reuse and recycling. [13-15] Implementing sustainable textile waste management strategies is essential for mitigating environmental impact.

Although textile recycling has improved in recent years, it remains largely commercially unviable. In Europe, only about one-fourth of textile waste is recovered or recycled, while the majority ends up in landfills. Alarmingly, only 1% of clothing is reintroduced into the production cycle. [16-18]

Before the emergence of synthetic fibers, natural fibers dominated the textile industry as the primary raw material. Synthetic fibers were first introduced in the late 1930s, and their usage has since surged, now accounting for approximately 70% of global fiber consumption. Among these, polyester has seen the most significant growth in the 21st century and is now the most widely used textile fiber. The production of polyester, derived from petrochemicals, requires substantial energy input, primarily sourced from non-renewable resources. [19-25] Similarly, the manufacturing of nylon fibers results in the release of greenhouse gases and other harmful pollutants into the atmosphere.

Water pollution is not limited to synthetic fibers; the production and disposal of natural fibers also have severe environmental consequences. Cotton is the most commonly used natural fiber in the textile industry, and its cultivation requires vast amounts of water around 2.6% of the world's total water consumption is attributed to cotton production. To meet global demand, large areas of land are cultivated, often requiring extensive pesticide and chemical use to enhance yields. Annually, around 11% of global pesticide consumption is linked to cotton farming, leading to severe environmental degradation. Although natural fibers decompose, the dyes and chemical treatments applied to textiles contribute to pollution and disrupt the biodegradation process. [26-28]

Throughout various stages of textile production from fiber processing to garment manufacturing and finishing numerous procedures negatively impact the environment. Carbon dioxide emissions from textile production are among the most significant environmental concerns. The raw materials used in fashion and textile industries are derived from agriculture, forestry, or fossil fuels, which are crucial sectors in addressing global warming. [29-34] The rapid fashion cycle and inadequate textile recycling practices also result in substantial economic consequences.

To counteract these challenges, global strategies and initiatives have been designed and implemented by experts. While these programs hold promise, achieving meaningful results remains difficult without regulatory enforcement. For instance, Textile Exchange has launched various programs aimed at reducing greenhouse gas (GHG) emissions from fiber and raw

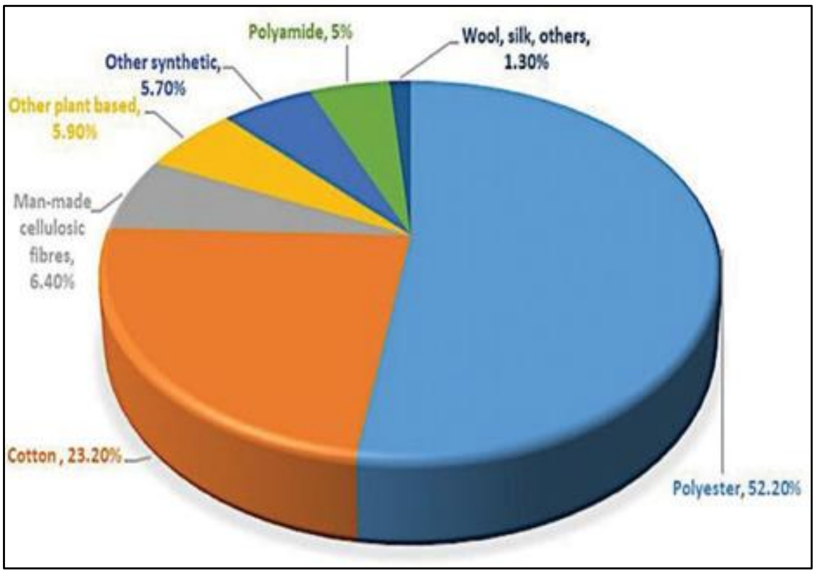

Figure 1 Fiber production share in the world in 2019

material production. Their goal was to decrease GHG emissions by 45% by 2030. However, achieving such targets requires large-scale measures, industry collaboration, and the integration of advanced technologies. According to projections, global GHG emissions from textiles should decline from 336 billion kilograms in 2019 to 203 billion kilograms by 2030. However, by 2021, emissions had risen to 340 billion kilograms, indicating that progress is currently moving in the wrong direction. Immediate action is necessary to address this issue. [35-38]

2. Types of textile waste

Textile waste generated by the apparel industry is generally classified into three categories: pre-consumer, post-consumer, and industrial waste.

- **Pre-consumer textile waste** refers to waste produced during the processing of natural, synthetic, or blended fibers into yarns, fabrics, and various textile products. This type of waste is easier to recycle than post-consumer waste because it is typically more uniform and contains fewer unknown contaminants. Unsold stock and returned items from both offline and online sales are also considered pre-consumer waste. However, some industry experts classify unsold stock and returns as industrial waste, as the fashion industry is responsible for their disposal. [39-42]
- According to the European Union (EU) Waste Directive, waste should be avoided as much as possible, and landfill disposal should only be considered when there are no other viable options. Clothing often contains multiple embellishments, linings, and accessories, making the recycling process more complex. [43-48]
- **Post-consumer textile waste** includes any garments or fabrics that have reached the end of their useful life due to wear and tear, damage, size changes, or shifts in fashion trends. These materials are typically disposed of in landfills or incinerated. A small portion is resold in second-hand markets in Europe or shipped overseas. However, economists and representatives from non-governmental organizations (NGOs) have raised concerns about second-hand clothing exports. [49-52] The influx of used garments into Asian and African markets has had a negative impact on their domestic apparel industries.
- **Industrial textile waste** is generated by commercial and industrial users, including carpets, hospital discards, filters, and conveyor belts. This type of waste is often classified as contaminated and, due to the complexity of its chemical treatments and collection methods, has a lower likelihood of being recycled. As a result, incineration and landfilling are common disposal methods for this category of waste. [53-54]

3. Economic and Environmental Impact of Textile Recycling

Ideally, 100% of waste generated by the textile and fashion industries should be recyclable, ensuring that no part of the fashion industry contributes to non-recyclable waste. However, in reality, a significant portion of textile waste is disposed of in landfills, with much of it being difficult or costly to recycle. As a consequence, many countries face economic and environmental challenges due to the mismanagement of textile waste.

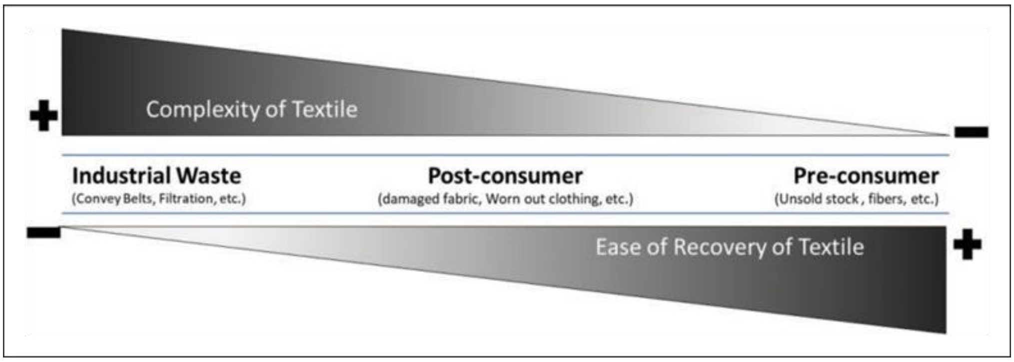

Figure 2 Various categories of textile waste and the difficulty of recycling them

4. Economic Aspects

As the world's largest producer of textiles and apparel, China is facing a significant crisis. Over the past few decades, China's industrial sector has experienced continuous growth, and its textile industry, including the production of synthetic fibers, has been no exception. Nearly two-thirds of the world's clothing is manufactured in Bangladesh. [55-58]

To address the issue of textile waste, the Chinese government encourages fashion-related businesses to recycle their textiles through mechanical and chemical processes. However, the lack of highly efficient recycling technologies limits the effectiveness of these efforts. In 2022, less than 20% of the 26 billion kilograms of textile waste in China was recycled. Similarly, in 2020, only 1.5 billion kilograms of the 22 billion kilograms of textile waste underwent recycling. In 2017, China managed to recycle 3.7 billion kilograms of textiles, while 26 billion kilograms were sent to landfills. The government has set a goal to increase the textile recycling rate to 25% by 2025 and 30% by 2030. [59-68]

In the European Union (EU), the textile industry generates approximately 16 billion kilograms of waste annually, with only about one-quarter being recycled, while the rest is sent to landfills. Various European institutions have established policies to regulate textile waste management, which EU member states are expected to adopt. These policies include Extended Producer Responsibility (EPR), which holds producers accountable for the recycling and disposal of textiles. In some cases, this is implemented through an EPR "tax." Since the introduction of this policy in France, the collection of post-consumer textiles has increased by an average of 13% per year. [69-75] The EPR framework also promotes research and development within the sector to address challenges faced by textile manufacturers and recyclers. Producer responsibility, along with separate collection and recycling initiatives, plays a crucial role in the success of EPR-based environmental policies.

In the United States, the majority of textile waste comes from clothing, though other sources, such as carpets, footwear, and tires, also contribute significantly. Recent trends indicate an increase in textile waste in the U.S. In 2010, approximately 13 billion kilograms of textile waste was generated, which rose to 16.9 billion kilograms by 2017. More than four-fifths of textiles discarded in the U.S. end up in landfills, with only around 15-20% being recycled or donated. [76-80] Among the world's leading economies, the U.S. disposes of more textile waste than any other country, with China ranking second.

5. Environmental Aspects

The textile industry consumes vast amounts of water, chemicals, and energy throughout various stages of production, from fiber processing to garment manufacturing. Waste generation is an inevitable byproduct of these activities. Each stage of a garment's life cycle is associated with key environmental parameters, including carbon emissions, water usage, chemical pollution, and fiber waste.

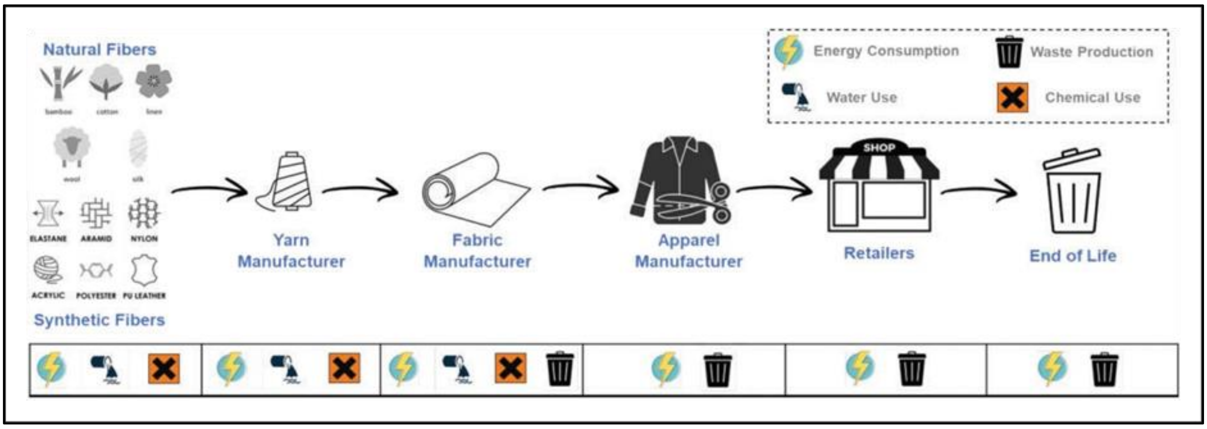

Figure 3 Schematic illustration of different stages of the process from production to consumption of clothing and its environmental effects

The globalization of supply chains within the textile and fashion industries has led to an uneven distribution of environmental harm across different regions. While developing countries with large textile industries often experience severe ecological degradation, developed nations are not immune to these effects. For instance, carbon emissions from textile production contribute to global warming, while water pollution from manufacturing processes can contaminate aquatic ecosystems. [81-84] Pollutants from textile industries may affect fish populations in production regions

6. Water Usage

The fashion industry is one of the largest consumers of water resources, significantly impacting global water supply and posing a major environmental challenge. Studies indicate that producing 1 kg of cotton—equivalent to a T-shirt and a pair of jeans—requires over 20,000 liters of water. Approximately 2.6% of global water consumption is attributed to cotton production, with around 44 trillion liters of water used annually for irrigation in textile production. [85-87]

Many countries that cultivate vast amounts of cotton suffer environmental consequences due to excessive water use. For instance, estimates suggest that about 20% of the water depletion from the Aral Sea is linked to cotton consumption in Europe. This exemplifies the severe environmental degradation resulting from human activities. [88-90] Unsustainable water practices have led to significant shortages of potable water and the introduction of toxic substances into aquatic ecosystems, causing irreversible damage to marine life.

During the dyeing and finishing processes in textile manufacturing, hazardous chemicals often contaminate wastewater. In countries with weak environmental regulations, these chemicals frequently seep into groundwater, leading to severe pollution.

7. Carbon Footprint

The textile industry ranks among the world's largest polluters. The fashion sector, encompassing the production of clothing worn by people worldwide, accounts for approximately 10% of global greenhouse gas (GHG) emissions. This is primarily due to its complex supply chains and energy-intensive manufacturing processes. Surprisingly, the textile sector contributes more GHG emissions than international aviation and the maritime industry combined. While aviation is responsible for 2.5% of global carbon emissions and shipping accounts for 2.2%, the impact of fashion is significantly higher. [91-95]

Most estimates of fashion's carbon footprint focus on production alone, often excluding transportation, retail operations, and product lifecycle impacts. A study on Swedish textile consumption revealed that approximately 14% of the fashion industry's total climate impact is associated with the usage phase of garments. The carbon footprint of the fashion industry extends beyond garment production and transportation, encompassing every stage of the supply chain, from fiber processing to disposal.

The high carbon footprint of fashion is driven by energy-intensive processes required to transform fibers into yarn, fabric, dyed textiles, and eventually, finished clothing. The energy used in these processes is primarily sourced from non-renewable fossil fuels, further intensifying environmental damage. In China, home to the world's largest textile industry, fashion production relies heavily on coal-based energy, making its carbon emissions surpass those of the European Union. [96-100]

With the rise of fast fashion and its emphasis on affordability, there is little incentive to invest in renewable energy solutions. Switching to sustainable energy sources would substantially increase production costs, discouraging many fast fashion businesses from adopting green alternatives. Additionally, synthetic fibers dominate the fashion industry due to their affordability and large-scale availability. However, garments made from synthetic fibers have significantly higher energy consumption and carbon footprints, as they are derived from petroleum-based raw materials.

Both the type of fiber and the production method impact the carbon footprint of textiles. For example, conventional cotton farming using industrial methods emits far more carbon dioxide than organic farming. Industrial cotton cultivation can generate up to 3.5 times more CO_2 emissions than organic cotton. [101-104] Nevertheless, even non-organic natural fibers produce considerably lower carbon footprints than synthetic alternatives. Substituting synthetic fibers with natural alternatives can significantly reduce emissions.

Among natural fibers, plant-based bast fibers such as jute, hemp, and flax are particularly beneficial, as they absorb atmospheric carbon and function as carbon sinks. This makes them highly effective in mitigating the industry's environmental impact.

8. Chemical Usage

The textile industry is heavily reliant on chemicals throughout the production process. Nearly 11% of global pesticide use and 24% of insecticide consumption are attributed to conventional cotton farming. Additionally, around 7% of all herbicides used worldwide are applied in cotton cultivation, surpassing any other crop.[105-108] In countries like the United States, China, India, and Brazil, excessive chemical use has led to severe soil degradation.

In yarn and fabric production, various chemicals, including lubricants, accelerators, antistatic agents, and solvents, are widely used. The dyeing and finishing processes further introduce a vast range of toxic substances. More than 80% of the chemicals used in European textile production are manufactured outside of Europe, meaning the environmental costs associated with their production such as water and energy consumption and carbon emissions are effectively "imported" alongside the chemicals themselves. [109-111]

The increasing use of antibacterial agents in textiles has raised concerns, as it can contribute to the development of antibiotic-resistant bacteria. This is a growing global health threat that requires careful regulation. Studies indicate that nearly 5% of commonly used antibacterial chemicals pose significant environmental risks. These substances can persist in the environment, bioaccumulate in living organisms, and potentially cause health issues such as allergies, illnesses, and even cancer.

Waterproofing chemicals used in textiles, which are often composed of highly stable fluoropolymers, have been detected in remote Arctic regions and even in polar wildlife. [112-115] This demonstrates how chemical pollutants from textile production can have far-reaching and global consequences.

One potential solution is the replacement of hazardous chemicals with safer alternatives. However, introducing new chemicals without thorough pre-implementation safety testing can be risky. For instance, long-chain perfluoroalkyl and polyfluoroalkyl substances (PFAS), commonly used in textile manufacturing, are being replaced with shorter-chain PFAS variants. However, insufficient research exists regarding the potential long-term risks of these substitutes. [116-118] While they may currently be classified as safe under existing regulations due to their lower toxicity, they could still pose environmental and health hazards in the future.

9. Textile Reuse and Recycling

Reducing the negative environmental impacts of textile waste has made textile reuse an increasingly popular option. Textile reuse refers to the process of using or adapting existing textiles instead of creating new products. It is widely recognized that reuse is more beneficial than recycling, particularly when the reuse phase can be extended for a significant period. Textile reuse provides various ways to extend the useful service life of textile products beyond their original owners, including repair, refurbishment, upcycling, and donation. [119-125] These practices help individuals and businesses reduce their environmental footprint while assisting those in need.

Once a product has been used for as long as possible and has potentially been reused by others, it should then be recycled. Fiber-to-fiber recycling can have a significant positive impact on the environment by reducing the need for virgin raw textile fiber production. Additionally, studies indicate that the production of recycled fibers consumes less energy and results in lower carbon dioxide emissions compared to the production of virgin materials. [126-131] Furthermore, recycling textiles is a far more sustainable approach than incineration or landfill disposal, both of which negatively affect the environment. Converting waste materials into textiles helps reduce water consumption since recycled materials typically require less water and generate fewer emissions than new raw materials.

Modern textile recycling is an essential component of waste management and can be categorized into four main types: upcycling, downcycling, closed-loop recycling, and open-loop recycling. Upcycling involves transforming materials into higher-quality or more valuable products, while downcycling refers to breaking materials down into lower-quality products. Closed-loop recycling uses recycled materials within the same product cycle, whereas open-loop recycling repurposes materials for entirely different applications, often resulting in downcycling. Each type of textile recycling plays a unique and crucial role in diverting waste from landfills. Open-loop recycling, such as converting recycled polyester garments into plastic bottles, is currently a more common source of recycled textiles than closed-loop recycling. [132-136] This process involves breaking down waste materials into their fundamental components, which are then used to create new products.

In contrast, closed-loop recycling focuses on reusing the same material repeatedly for the same type of product, such as fiber-to-fiber recycling. While closed-loop recycling is considered more environmentally friendly, open-loop recycling has its advantages, particularly when closed-loop recycling facilities are unavailable. For instance, open-loop recycling can help reduce the amount of waste sent to landfills while also decreasing the demand for virgin materials in other industries. Both closed-loop and open-loop recycling contribute to reducing greenhouse gas emissions by lowering the energy required for new product manufacturing from virgin materials. A study published in the *Journal of Resources, Conservation & Recycling* found that open-loop recycling can also provide economic benefits, including job creation and financial incentives for waste processors. [137-139]

Closed-loop recycling is an efficient method for recovering and reprocessing raw materials used in polymer-based products, sometimes allowing for the production of materials of the same quality as virgin ones. This approach reduces reliance on natural resources and lowers pollution levels, thus promoting long-term sustainability. Different types of reuse and recycling classifications are illustrated in Figure 4.

10. Textile Recycling Technologies

A range of technologies can be employed to promote and facilitate the recycling and recovery of textile waste. These technologies have the potential to provide effective solutions for minimizing environmental impact and reducing landfill waste. The following sections explore key mechanical, chemical, and bio-chemical recycling technologies.

10.1. Mechanical Recycling Technologies

Mechanical recycling is generally recognized as the most straightforward and efficient method of textile recycling. This process can be divided into two main approaches. The first approach involves cutting, shredding, and carding/garneting textiles, which can be applied to most textile materials. The fibers obtained through this process tend to be shorter than virgin fibers, resulting in reduced strength and lower yarn quality. These recycled fibers can be spun into yarn for use in woven or knitted fabrics or directly used in nonwoven materials. [140-144] Additionally, shredded fiber-based products are often referred to as “shoddy” fibers, commonly used in applications such as rugs, carpets, insulation, industrial fillings, and building materials. For instance, shredded textile waste can be compressed and heated into plates used for soundproofing and thermal insulation.

Within mechanical recycling, garnet machines play a crucial role in fiber extraction. These machines utilize sharp metal teeth to break down fabrics and separate individual fibers. While garneted fibers are generally of lower quality than virgin fibers, advancements in machine technology have enabled the recovery of higher-quality fibers, making them suitable for wearable-grade textiles. [145-148] The primary limitation of mechanical textile recycling is that the quality of the resulting fiber is often inferior to virgin fiber.

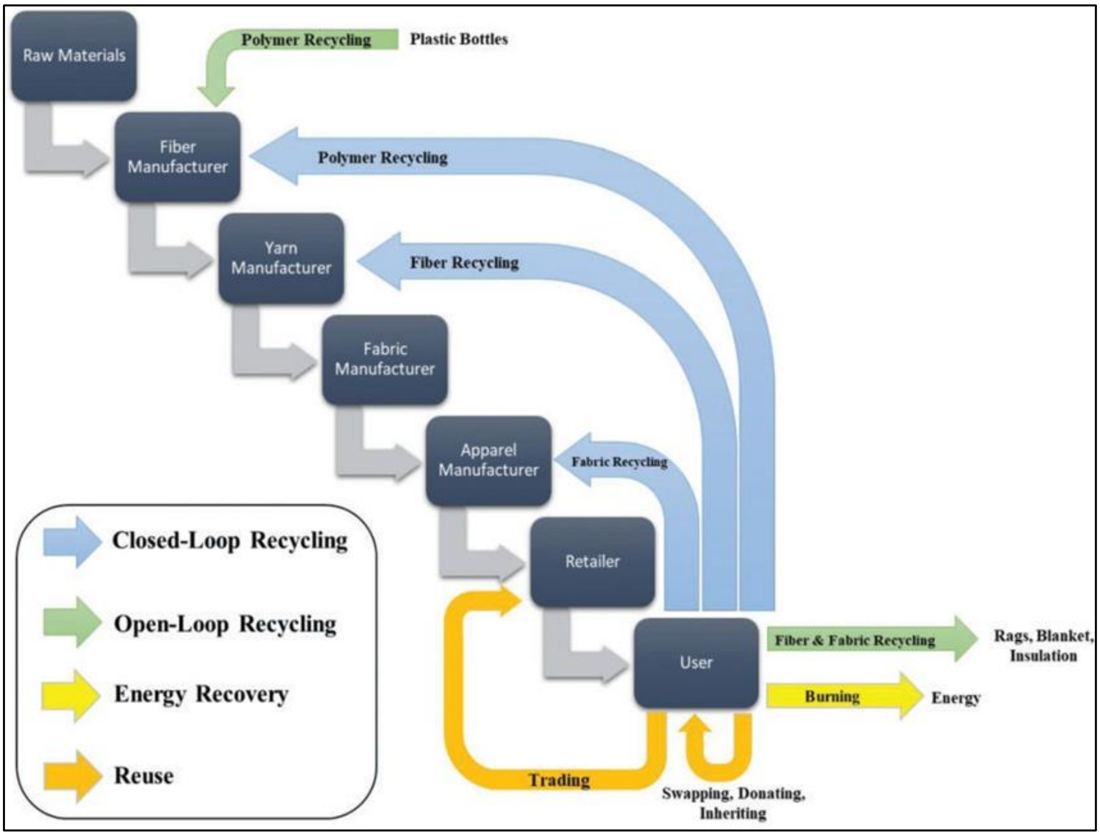

Figure 4 Classification of reuse and recycle routes

The second approach involves **thermo-mechanical processing**, commonly used in the open-loop recycling of plastic bottles into recycled polyester (or nylon) fibers. Thermo-mechanical technologies are a promising method for recycling thermoplastic textile materials such as polyester and nylon. The process involves mechanically breaking down waste materials, followed by heating, agitation, and filtration to separate impurities and extract fibers. This method can produce high-quality recycled materials suitable for a wide range of applications.[149]

While the quality of thermo-mechanically recycled textiles is often superior to that of mechanically shredded textiles, current research on fiber-to-fiber thermo-mechanical recycling remains limited. The effectiveness of this process largely depends on the quality of the feedstock used. Thermo-mechanical recycling is faster and more cost-effective than chemical recycling, as it does not require chemical solvents. Additionally, it consumes less energy and results in less degradation compared to many other mechanical recycling techniques

10.2. Chemical Technology

In general, chemical processing involves converting textile waste into oligomers and monomers and their subsequent repolymerization. Depolymerization processes have become increasingly popular in waste management when treating synthetic polymers. This process effectively breaks down polymers into monomers or oligomers, which can then be more easily managed and reused. Textile waste can be transformed into valuable resins like nylon and polyester, which can then be reformed into their original resin state from monomers or oligomers. Depolymerization methods include hydrolysis, ammonolysis, glycolysis, solvolysis, and metanalysis. For example, metanalysis is used in the production of nylon 6, which is typically converted into caprolactam or lactam, while hydrolysis can also be used to recycle nylon 6,6. Table 1 shows various depolymerization methods and their output products.

Polyester is the most commonly used synthetic fiber in the textile industry, and thus polyester recycling can help promote sustainable development in this sector. By recycling these materials, we can reduce our environmental impact and contribute to a more sustainable future. Ochi et al. have developed a highly efficient two-step process to separate cotton and polyester blends. In this process, blended fabrics are treated with an acid bath followed by various mechanical treatments. This method has successfully separated polyester fabric with a high recovery rate. While this development is significant, it will always be cheaper and more efficient to recycle fibers in pure forms rather than mixed ones. [150-151]

Man-made cellulose (MMC) fibers refer to synthetic fibers made from plant materials that retain cellulose, typically derived from wood, but can also be produced from waste cellulose (e.g., recycled). Through a chemical process, discarded cellulose fibers are subjected to intense treatment to create a structure made of dissolved cellulose fibers. These fibers are then extruded into filaments or cut into fibers and woven into fabrics. Some of the most commonly used MMC fabrics include rayon (viscose), lyocell, and modal. However, it is also possible to produce MMC fibers from other plant sources such as bamboo, husks, and even agricultural waste. MMC production is widespread, and it is recognized as the third most common fiber globally, with an annual production of approximately 7.1 billion kilograms. It accounts for about 6.4% of the total fiber production worldwide, contributing around 25 billion US dollars in market value, and is growing steadily. [152-154]

Table 1 Depolymerization techniques of nylon and polyester and their products

	Products			
	Method: glycolysis	**Method: metanalysis**	**Method: hydrolysis**	**Method: ammonolysis**
Polyester Nylon 6	Bis(2-hydroxyethyl) terephthalate + oligomers	Dimethyltryptamine + ethylene glycol Caprolactam	Terephthalic acid + ethylene glycol	p-Phenylenediamine
Nylon 6,6		Adipic acid + hexamethylenediamine	Adipic acid + hexamethylenediamine	

Chemical recycling is generally more expensive than mechanical recycling and virgin fiber production. In chemical recycling, mixed fibers, dyes, finishing, and processing agents are separated from valuable feedstocks. During this process, fibers may degrade, and the use of toxic chemicals as solvents is not without its consequences. Discovered that polyester chemical recycling required 6599 kWh/ton of textile input for energy and heat. In contrast, cellulose-based textiles required 7479 kWh/ton of textile input. This indicates that polyester is more energy-efficient compared to cellulose-based materials in chemical recycling processes.

10.3. Biochemical Technologies

One environmentally friendly method for handling cellulose-based textile waste is the biochemical process, which uses enzymes to convert polymeric chains into monomers. Enzymes are biocatalysts that enhance the efficiency and rate of chemical and biochemical processes. Biochemical processes generally start with acidic or alkaline pretreatments that break down the fiber structure. Cellulose consists of two parts, amorphous and crystalline. Acidic pretreatment creates hydrolysis of the amorphous portion, and enzymes reduce the crystalline part. Acidic pretreatment works by breaking the intermolecular and intramolecular bonds in cellulose molecules, providing more space for enzymatic treatment. As a result, it can significantly improve conversion rates compared to traditional chemical methods and allow for more efficient use of resources. Alkaline pretreatment is an effective way to improve the efficiency of cellulose-based bioconversion processes. Alkaline pretreatment typically involves various chemicals such as sodium hydroxide, potassium hydroxide, and calcium hydroxide. [155-157]. Cellulosic enzymes are used for enzymatic hydrolysis of cellulose, effectively breaking down glycosidic bonds in cellulose. Biochemical recycling works not only for natural cellulose-based materials but also for synthetics like polyester. Pretreatment is necessary to ensure effective enzymatic hydrolysis of synthetic, blended, or dyed cotton. Without this, the process would not yield the desired results. Monomers can be reused in the production of polymers or other products. However, during the hydrolysis process, large protein molecules cannot penetrate polyester materials, meaning hydrolysis only occurs on the surface components, which limits the environmental potential of the process, making it difficult to use effectively.

Biotechnological methods for regenerating monomers from synthetic fiber blends are hindered by limited enzyme accessibility and a lack of efficient existing enzymes capable of significantly degrading man-made synthetic materials. The absence of hydrolysable functional groups and heteroatoms like oxygen and nitrogen in carbon-carbon backbone polymers hinders biodegradation by microorganisms. This limitation is particularly evident in certain textile polymers, such as healthcare protective textiles, which are challenging to recycle using biocatalysts. Although polypropylene can undergo some oxidative degradation by laccases (EC 1.10.3.2) produced by *Pycnonotus cannabusiness*, previous studies have shown that only low molecular weight compounds are released for minimal weight reduction. For polyesters, hydroquinone peroxidases (EC 1.11.1.7) have demonstrated some degradation activity. Additionally, certain insects, with the help of gut microbiota, have shown the ability to depolymerize polystyrene foams. However, the lack of identified or isolated biocatalysts limits their widespread industrial applications. [158-159]

11. Resource Recovery from Recyclable Textiles

When it is not possible or economically sustainable to recycle textile materials, some of their resources can still be recovered through methods such as thermal recovery, anaerobic digestion, fermentation, blending, and other techniques. Table 2 shows the technologies used for recycling textiles and their potential final applications.

Table 2 Textile wastes recycling and their application

Technology	Material	Process	Output	Reference
Mechanical	Cotton	Cutting and shredding waste	Recycled fiber	18
Mechanical	Cotton	Shredding	Sound insulation	99
Mechanical	Cotton/polyester	Using compression molding technique	Composites	100
Mechanical	Cotton	Using compression molding technique	Composites	101
Mechanical	Acrylic/wool	Using needle-punching method to produce nonwovens	Thermal insulation	102
Mechanical	Acrylic	Reinforce acrylic waste between walls	Thermal insulation	103
Chemical	Cotton, acrylic, cotton/polyester	Carbonization	Biochar	104
Chemical	Cotton	Wet spinning	Cotton fiber	105
Chemical	Cotton	Dry-jet wet spinning	Cellulose fiber	12
Chemical	Cotton/nylon	Dissolution of fabrics in an ionic liquid, 1-allyl-3-methylimidazolium chloride, and subsequent separation	Cellulose films and nylon fiber	106
Chemical	Lyocell	Carboxymethylation reaction to produce fiber hydrophobic, crosslinking reaction	Heavy metal adsorbent	107
Biochemical	Cotton	Alkali pretreatment and hydrolysis	Ethanol	108
Biochemical	Cotton	Alkali pretreatment and hydrolysis	Ethanol and polyester	93
Biochemical	Wool/polyester	Enzymatic treatment	Polyester	109
Biochemical	Polyester/cotton and polyester/viscose	Dissolving cellulose in N-methylmorpholine-N-oxide solution and hydrolyzing	Ethanol and biogas	110
Thermal	Acrylic	Pyrolysis	Activated carbon	111

11.1. Thermal Recovery

Recycling mixed or composite textiles is often one of the most challenging processes, but it is not an issue in thermal recovery systems. Thermal recovery is a downcycling process where waste textiles are converted into energy sources. Textile waste, as a rich energy source, is composed of materials that can be used in combustion, pyrolysis, gasification, and incineration techniques, which are the most common methods for thermal recovery. Combustion involves a set of exothermic chemical reactions between fuel and oxygen that produce heat and energy. The pyrolysis process is the decomposition of organic material in the absence of oxygen. This method can help reduce waste sent to landfills, but it is less preferred since there is no possibility of reuse or replacement of virgin resources.[160]

11.2. Anaerobic Digestion of Textile Waste

Anaerobic digestion is a widely used method for treating biodegradable organic waste to produce biogas, a potential eco-friendly energy source. This method has gained popularity due to its efficiency in recycling organic waste and generating renewable energy. Cotton, which has over 50% cellulose content, can be a potential material for biological conversion. Various pre-treatment techniques, including mechanical, thermal, chemical, and biological processes, as well as the integration of multiple treatment technologies, can optimize the digestion process and significantly improve the biodegradation of complex organic materials in anaerobic systems. Pre-treatment increases the quality and production of biogas and improves the quality of biosolids.

11.3. Ethanol Fermentation from Textile Waste

The potential of cotton waste for ethanol production has been investigated since 1979, when Texas Tech University began experimenting with this technology. Cotton gin waste, also known as cotton gin trash, is a byproduct of the cotton ginning process. This waste material can be used to produce ethanol, a renewable fuel that can be blended with gasoline to reduce fossil fuel emissions and dependence. The process involves breaking down the cellulose in cotton gin waste into simple sugars, which are then fermented into ethanol. This method of producing ethanol from agricultural waste offers a sustainable solution that reduces waste and provides an alternative energy source. Several studies have shown that cotton gin trash has significant potential for ethanol production, making it a promising feedstock for biofuel production. The production of ethanol from textile waste can be enhanced through alkaline pretreatment of polyester/cotton blends, leading to higher yield, quality, and cost-effectiveness. Researchers have determined that the maximum optimal ethanol yield of 70% can be achieved using simultaneous saccharification and fermentation processes with sodium hydroxide/urea pre-treatment at -20°C. This groundbreaking method has proven to be the most desirable and efficient, offering excellent potential for sustainable energy production.[161]

11.4. Cotton Waste from Textile Factories

Cotton waste from textile factories can be effectively treated with acid and alkali to reveal hidden sugars. These sugars can then be broken down by cellulase enzymes produced by Fusarium species, enabling effective recycling of this waste. Acid pre-treatment enhances enzyme activity and increases sugar production during fermentation with Saccharomyces cerevisiae. On the other hand, alkali pre-treatment breaks down cellulose bonds and increases the surface area of the fibers, improving enzymatic hydrolysis efficiency. Viscose textile waste, which contains a higher cellulose content than cotton, is a more favorable source for ethanol synthesis, resulting in higher ethanol yields compared to cotton. Studies indicate that alkaline pre-treatment is not essential for viscose fiber waste, but it is recommended for cotton fiber waste to achieve optimal efficiency.[162] Comparative research suggests that using viscose fibers instead of cotton leads to faster enzymatic hydrolysis rates and higher fermentation yields, with the differences attributed to the fine microcrystalline structural variations between the two fibers.

11.5. Textile Composting

Composting is a natural process that uses the power of biodegradation to break down organic waste, such as cotton waste, into nutrient-rich soil supplements. This process helps return valuable nutrients to the soil and can be used to restore nutrient-poor soils after agricultural practices or as an addition to garden beds. It is also known for improving soil structure, reducing erosion, and helping with water retention, making it an incredibly useful tool for all types of gardening and farming. Composting is an efficient, low-tech, and bio-oxidative process that can reduce organic waste by up to half during its active phase. It helps create a sustainable cycle and provides an excellent nutrient source for plants. Cotton waste disposal presents a huge challenge, and composting offers a better solution than landfills. Both composted and vermicompost cotton waste can be beneficial as a nutrient source.[163] When a cotton waste substrate was tested, the bacterial diversity in compost and vermicompost samples was almost the same. However, the bacterial disintegration density was higher in vermicompost samples compared to compost, resulting in greater humus production.

11.6. Composting Used Wool Waste

Composting is an ideal method for disposing of used wool because it not only sanitizes the waste but also reduces its environmental impact. It stabilizes organic waste and produces organic fertilizer, promoting circular agriculture. Compared to animal waste, composting wool waste with rock phosphate results in a higher-quality compost. Based on these findings, it is noted that using slurry as an inoculum to catalyze the degradation of resilient materials like wool waste is advantageous.[164] Specifically, when a mixture of 10% animal slurry (based on dry weight) and 2% rock phosphate is used, it results in a higher-quality compost than using various ratios of manure and rock phosphate. As a result, it is recommended to use slurry as an inoculum with 10% dry weight and 2% rock phosphate for effective wool waste composting. This environmentally friendly and cost-effective method has been successfully tested in Texas, helping to reduce the amount of waste that ends up in landfills.

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12. Conclusion

The rapid expansion of the population, rising living standards, increasing industrialization, suppressed wages for textile and garment workers, and the affordability of cheap clothing have collectively contributed to the global rise in textile consumption. This surge has led to a concerning increase in textile waste being discarded in landfills worldwide, along with illegal disposal of textiles. The growing volume of textile waste is forming a looming concern. Addressing this issue is vital for the protection of our planet and its limited resources. Both economic and environmental sustainability principles must be integrated to establish a comprehensive textile waste management framework, and immediate action is needed to set up such a structure. By implementing such schemes, businesses and enterprises can reduce their carbon footprints, minimize energy consumption, and contribute to a more sustainable future. Furthermore, waste management initiatives hold the potential to optimize fabric production processes and reduce the environmental costs associated with waste disposal.

The use of textile materials should be maximized by focusing on extending their lifespan through reuse practices. Recycling should only occur when reuse and repurposing options have been exhausted. Mechanical methods like shredding and thermo-mechanical recycling are often the costliest but may degrade the quality of recyclable materials compared to virgin counterparts. Although chemical recycling methods are more expensive than mechanical ones, they show promise in maintaining the quality of virgin fibers. When closed-loop recycling systems are ineffective, downcycling into products that replace virgin materials in other industries becomes a preferable alternative. Methods like incineration for energy production should only be considered as a last resort due to the inadequate processing facilities available. Landfilling textile waste is an unsuitable approach for managing it.

Despite the importance of textile recycling, resource recovery, and composting, several challenges persist in this domain. Fiber blends make reprocessing more challenging and expensive, and should be avoided where possible. The harmful chemicals in textile waste complicate recycling processes, reduce compost viability, and pose threats to both human health and the environment. Additionally, the lack of awareness among consumers about the impact of their use and the significance of textile recovery requires attention and education. Economic factors have also hindered the trend of textile waste recycling. The costs associated with implementing recycling processes and the lack of economic incentives to encourage participation have contributed to the opaque development of this sector. However, overcoming these challenges and promoting sustainable practices in fashion waste recycling is crucial. EPR schemes hold potential to fund and improve the infrastructure for collection, sorting, and recycling.

This review article offers an extensive investigation into textile waste in the fashion industry, highlighting the technologies used, applications of recyclable products, recovery methods, and the obstacles encountered in the process. By understanding these aspects, stakeholders can work towards developing efficient and sustainable strategies to address the pressing issue of textile waste. However, given our current progress and the experiences of other sectors, changes in legislation and taxation may be necessary to provide the required momentum to meet global sustainability goals.

Compliance with ethical standards

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