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Textile Waste Management-Innovative Separation Techniques

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Abstract

Characterizing the fibre composition and removing them from material blends is essential in implementing an effective fibre recycling system. This study delves into innovative methods for handling textile waste in response to environmental challenges from the textile industry. It covers traditional and modern separation techniques, including mechanical, chemical, biological, electrostatic, and laser-induced breakdown spectroscopy. Emphasizing sustainable practices in textiles is crucial to combat waste accumulation and environmental harm caused by fast fashion. Advanced separation methods are key to promoting textile material recycling and upcycling for a circular and eco-friendly fashion sector. Implementing these strategies can reduce the industry's environmental impact, decrease landfill waste, and contribute to a more sustainable future for the textile industry and the planet.

Keywords: Clothing; Fibre; Textile Waste; Fashion; Textile Material Recycling; Eco-Friendly Fashion; Environmental Health; Respiratory; Cardiovascular Health; Dyes; Synthetic Fibres; Fabrics; Laundry Hampers

Introduction

While providing clothing and other necessities, the textile industry has become a major contributor to waste and environmental harm. The rise of fast fashion, characterized by cheap, trendy clothes quickly brought to market, is a major driver of this waste generation problem. The constant desire for new styles and the low cost of these garments lead to impulsive buying and frequent discarding [1-3]. It is a vicious cycle that keeps the waste mountain growing, as seen in (Figure 1).

Figure 1: Textile Waste Accumulation.

The current linear fashion system exerts significant pressure on precious resources like water, generating substantial environmental contamination and societal repercussions on a global scale [4,5]. Specifically, low-quality, imported clothing often faces immediate disposal due to its inadequacy, resulting in its accumulation in landfills and open dumps. This decomposition process releases gases and chemical leachates, polluting air, soil, and groundwater, posing detrimental threats to environmental health and human wellbeing. Furthermore, discarded clothing can obstruct drainage systems, exacerbating flooding events and facilitating the spread of waterborne diseases, a concern amplified by increased flooding in the Global South due to climate change. In resource-constrained environments, open burning of unwanted clothing becomes common, contributing significantly to air pollution with detrimental consequences for respiratory and cardiovascular health [1].

The world's insatiable appetite for fashion has fostered a burgeoning paradox-a booming industry alongside a catastrophic environmental and social burden. The global textile waste problem is no longer a looming threat but a tangible reality, reaching an alarming 92 million tons annually [6]. The environmental consequences of this unchecked waste are far-reaching and direct:

a) **Polluted Landscapes:** Textile production and waste disposal contaminate water bodies with dyes and chemicals, wreaking havoc on aquatic ecosystems.

b) **Microplastic Menace:** Synthetic fibres shed from discarded clothes infiltrate our oceans and food chain, jeopardising marine life and human health.

c) **Landfill Legacy:** Mountains of textiles decompose anaerobically, releasing potent greenhouse gases like methane and occupying valuable land that could be repurposed.

d) **Exploitative Practices:** Garment workers in developing countries often face abysmal working conditions, low wages, and even exploitative child labour.

e) **Economic Inefficiency:** Discarded textiles represent a colossal waste of resources and missed opportunities for circularity and sustainable practices.

Textile Waste types

Textile waste is categorized into pre-consumer and post-consumer. Pre-consumer waste, generated during production, is generally easier to recycle because its composition is known. On the other hand, post-consumer waste comes from items like used clothing, carpets, curtains, and other textiles discarded by consumers, including through second-hand markets [7-10].

Pre-Consumer Waste

Pre-consumer textile waste encompasses a diverse array of materials discarded before reaching the consumer's hands.

The Spinning and Weaving Stage

a) **Yarn Waste:** Imperfectly spun yarns, discolouration, and leftover scraps are generated during the spinning processes.

b) **Fabric Offcuts:** Excess fabric trimmings discarded after garment cutting, often in irregular shapes and sizes.

c) **Defective Fabrics:** Fabrics with printing or dyeing flaws deemed unsuitable for final products.

Garment Manufacturing

a) **Cut-and-Sew Waste:** Fabric scraps generated during garment assembly, often too small for further use.

b) **Overproduction:** Unsold inventory exceeding market demand, accumulating in warehouses.

c) **Sampling Waste:** Unused fabrics and garments from prototype development and sample creation.

Design and Development

a) **Textile Swatches:** Leftover samples from fabric selection and design processes.

b) **Colour and Print Trials:** Discarded fabrics used for testing dyes, prints, and finishes.

c) **Unsold Prototypes:** Experimental garment designs not approved for mass production.

Other Contributors

a) **Packaging Materials:** Plastic wrap, cardboard boxes, and other packaging discarded post-production.

b) **Transportation Damage:** Fabrics are damaged during transportation between production stages or to retailers.

c) **Deadstock Fabric:** Unused fabrics from previous seasons accumulate in storage.

Post-Consumer Waste

Post-consumer textile waste, the unwanted fabrics that accumulate after we've worn and discarded them, presents a significant environmental challenge. Understanding its sources is crucial for tackling this issue effectively. Here is a breakdown of the main culprits [11].

a) **Discarded Clothing and Textiles:** This includes garments discarded due to wear and tear, fading, or changing trends. Textiles with rips, tears, or stains are often unusable in their current state and are discarded.

b) **Fast fashion casualties:** Clothes worn only a few times before being tossed aside due to trends, poor quality, or lack of repair knowledge. Imagine overflowing donation bins and landfills filled with barely used garments. Unwanted styles and

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sizes: Clothes that no longer fit, flatter, or suit our taste end up in the discard pile. A closet graveyard of forgotten fashion choices.

c) **Damaged and worn-out items:** Ripped jeans, faded shirts, and moth-eaten sweaters eventually end their wearable lifespan. Textile ghosts haunt our laundry hampers.

d) **Microfibres:** shed during washing of our clothes, especially synthetic ones. Washing conditions and friction are the key factors that release thousands to millions of microfibres per washing cycle. amounting to tons of pollution annually. In addition, chemicals and dyes are also released from our clothes washing, contributing to effluent load.

Household Textiles

a) **Bedding and towels:** Sheets, blankets, and towels lose their fluffiness and absorbency over time, often ending up in landfills rather than recycled.

b) **Curtains and upholstery:** Outdated patterns or faded colours motivate us to replace these larger textiles, generating bulky waste.

c) **Rugs and carpets:** Worn-out carpets or unwanted rugs contribute to textile waste, especially since synthetic materials often lack recycling options.

Industrial and Institutional Sources

a) **Hotel and hospital linens:** large quantities of sheets, towels, and uniforms discarded regularly by these sectors pose a significant waste challenge.

b) **Military and workwear:** Uniforms and work clothes can get damaged or outdated, creating a stream of industrial textile waste.

c) **Production scraps and unsold merchandise:** Manufacturers and retailers generate post-consumer waste through overproduction, damaged goods, and end-of-season items.

d) **Machinery:** To run smooth operations, many machine parts must be replaced or repaired during garment manufacturing or processing. Such parts are mechanical parts, hardware nut bolts, lubricant oils, connector wirings, vessel assemblies, etc. Materials used to clean spillages, like chemicals and machine oils, also generate side wastes.

Separation Technologies

The circular economy is hampered by the complexity of textile waste, often found in mixes like polyester/cotton, polyester/viscose, polyester/wool, nylon/wool, linen/silk etc. Recycling and recreating as a new product, therefore, become challenging. Separation of textile waste must be done effectively to facilitate recycling. Recovering valuable resources, reducing the quantity of material dumped in landfills, and enabling recyclable materials to find new uses depend on separating various constituents in waste streams. Today's market offers a vast array of sorting and separating technologies.

Mechanical separation

Mechanical textile waste separation refers to using physical methods to sort and separate different fabric and fibres from each other. This is an essential stage in the textile recycling process, as it directly impacts the efficiency and quality of the recycled material.

Size Separation

It uses screens, drums, or sieves to separate textiles based on size and shape. Efficient for sorting large pieces from smaller ones but may not be effective for separating fibres of different thicknesses.

Air-assisted separation of materials

This technique uses air to separate different materials, which include

a) **Air tables:** These are vibrating tables with an airflow that can separate lighter materials (typically synthetic fibres) from heavier materials (such as cotton).

b) **Air classifiers:** These use a controlled airflow to separate particles of different sizes and densities. They can be used to separate different types of fibers or to remove dust and other contaminants from textile waste.

c) **Cyclones:** These use centrifugal force to separate particles from air. They often remove dust and other debris from industrial processes [12].

d) The specific type of air separation used in textiles will depend on the desired outcome and the materials involved [13].

Density separation

Utilizes liquids of varying densities to float or sink different fibre types based on their buoyancy. Effective for separating blends with significant density differences but requires careful selection of liquids and can be messy to implement [14].

Near-infrared (NIR) technology

NIR radiation lies in the 750 to 2500 nm wavelength range, just beyond the visible spectrum. Specific molecules and materials absorb NIR light at unique wavelengths, creating a "fingerprint" that can be used to identify their composition. By analysing light that is reflected or transmitted through textile samples, NIR spectroscopy can disclose the chemical composition of the materials. Nowadays, chemometric approaches are primarily used to construct NIR analysis models, and not many studies have been done on integrating deep learning into NIR modelling [15,16].

Based on NIRS technology, an online NIR qualitative identification model of 13 kinds of waste textiles is established

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by CNN and Baidu Paddle platform. This model can be applied to the self-developed online NIR high-efficiency recognition and automatic sorting device for fibre products to provide an intelligent, efficient, eco-friendly, and non-destructive identification and sorting technology for grading recovery and high-value reuse of waste textiles. This device can perform the online efficient identification and automatic sorting of 13 kinds of waste textiles [17] (Figure 2).

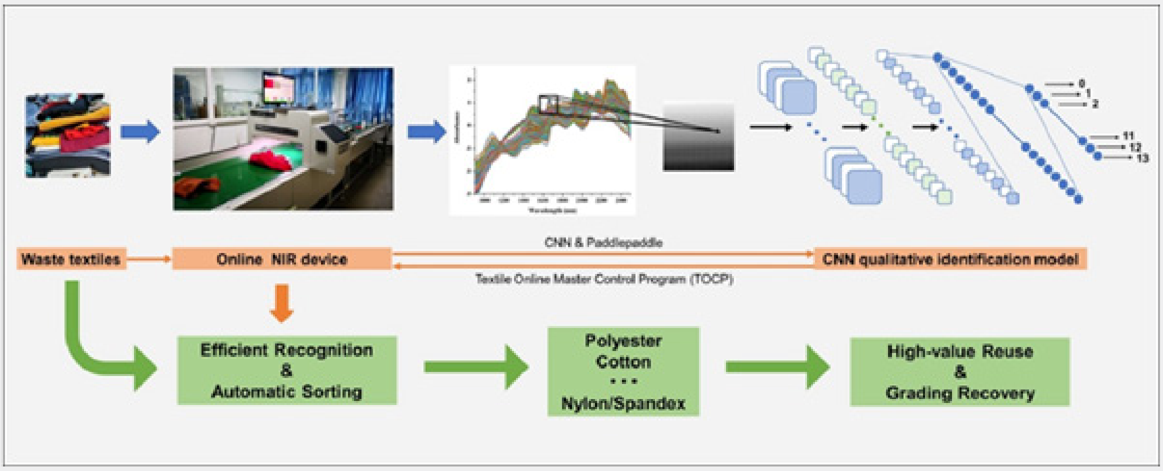

Figure 2: NIR qualitative identification model.

NIR sorting benefits

a) Fiber type identification: Different fibers, like cotton, polyester, nylon, and wool, have distinct NIR absorption patterns. NIR can accurately identify and differentiate these fibres, even in blends.

b) Dye and chemical detection: NIR can identify the presence of dyes, finishes, and other chemicals used in textile processing, which is crucial for proper recycling or disposal.

c) Contamination assessment: NIR can detect the presence of non-textile materials like zippers, buttons, or plastics, enabling their removal for pure fiber recovery.

This is an effective method for separating textile waste which offers high accuracy and precision for complex blends but requires sophisticated equipment and can be expensive (Figure 3).

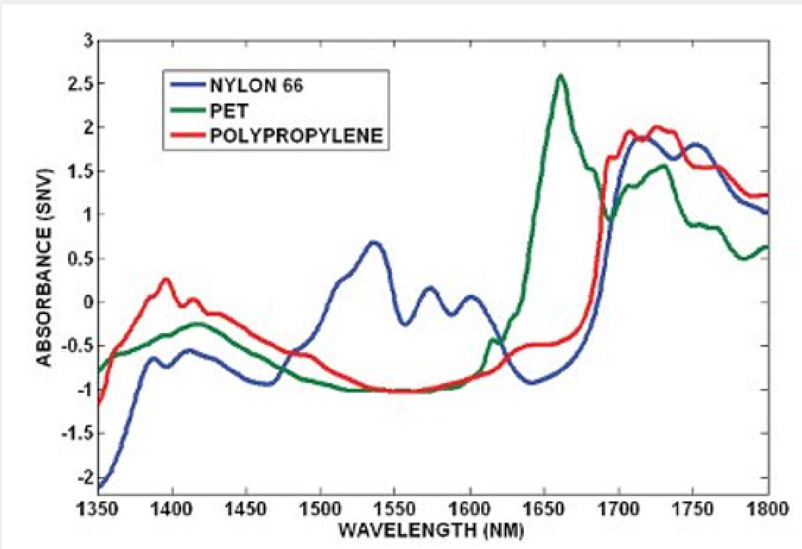

Figure 3: Near Infrared Spectra of Different Polymers.

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Colour sorting

It employs Sensor-based sorting: Optical sensors detect and analyze colour wavelengths, automatically sorting textiles into predefined categories. This method is fast and efficient but might struggle with subtle variations. Useful for sorting pre-consumer waste with consistent colour palettes but less effective for post-consumer textiles with diverse colours and patterns [18].

Chemical separation

Chemical separation is a growing area of research in textile waste recycling. It offers several advantages over traditional mechanical methods, particularly for blended fabrics and complex materials. These methods leverage the inherent chemical properties of different fibres and additives to achieve precise and efficient segregation.

a) **Solvent-Based Separation:** This method uses specific solvents to dissolve specific fibers. For example, cotton can be dissolved in a solvent like NMMO (N-methyl morpholine N-oxide), or cuprammonium hydroxide, separating other components like polyester. In the recent study on the separation process for elastane from polyester/elastane and polyamide/elastane textile waste, six different organic solvents (Cyrene, DMAc, DMF, DMSO, GVL, NMP) were selected and investigated. Solvent dimethyl sulfoxide (DMSO) was better and ran circularly within a three-step purification. Principle component analysis (PCA) of spectroscopic measurements (ATR-FTIR) revealed excellent results for the recovered polyester and polyamide [19,20].

b) **Chemical Degradation:** Controlled chemical reactions selectively break down certain fibres, allowing for targeted removal. Picture wool decomposing under specific conditions while leaving cotton unharmed, opening recycling avenues for mixed fabrics.

c) **Depolymerization and Repolymerization:** This advanced technique breaks down polymer chains of specific fibres like polyester or nylon into smaller molecules and reassembles them into virgin-like materials. Think of transforming discarded polyester clothes into brand-new bottles, revolutionizing plastic waste management.

d) **Chemical Modification:** Functionalization of specific fibres through targeted chemical reactions alters their properties, facilitating easier separation using existing mechanical methods. Imagine coating cotton with a special chemical that makes it readily distinguishable from polyester during air-jet separation (Figure 4).

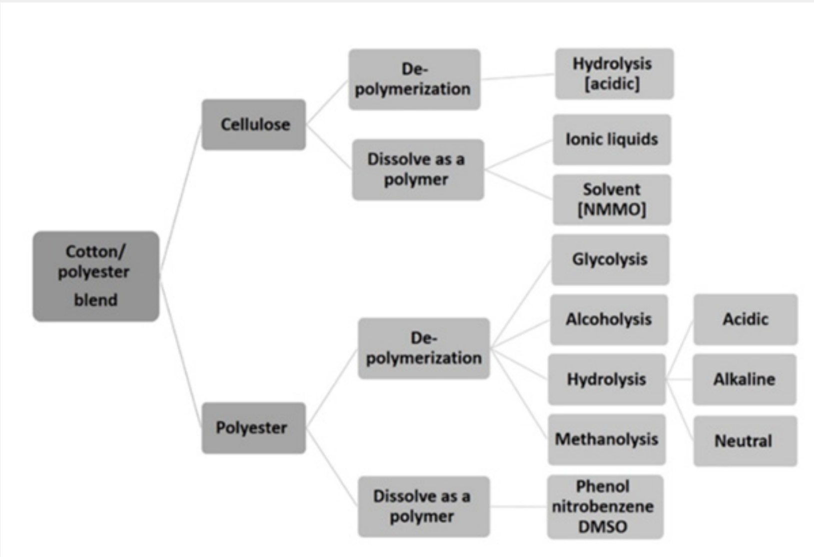

Figure 4: Chemical approaches to separate cotton/ polyester blends.

Biological separation

Traditional textile waste separation methods often rely on energy-intensive mechanical or chemical processes. However, a bio-inspired revolution is emerging, harnessing the power of microorganisms to achieve precise and sustainable material segregation. Biological separation utilizes enzymes and fungi with targeted biodegradation capabilities. These microscopic actors selectively break down specific fibre types within a blended textile, enabling efficient separation of cotton from polyester, wool from nylon, and other combinations. This targeted approach minimizes collateral damage to desired materials, resulting in purer recycled fibres compared to traditional methods. The process includes:

a) **Pre-treatment:** Textile waste is often pre-treated to improve enzyme accessibility and efficiency. This may

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involve mechanical shredding, chemical washing, or physical modifications.

b) Enzyme selection: Specific enzymes are chosen based on the targeted fiber types and desired breakdown products. For example, cellulases digest cellulose (found in cotton), while laccase enzymes break down lignin (present in natural fibers) [21].

c) Enzymatic hydrolysis: The selected enzymes are introduced to the pre-treated textile waste, where they catalyze the deconstruction of targeted fiber components. This process typically occurs under controlled temperature and pH conditions.

d) Product recovery: The resulting breakdown products, such as glucose from cellulose or monomers from polyester, can be further processed or refined into various valorized materials [22] (Figure 5).

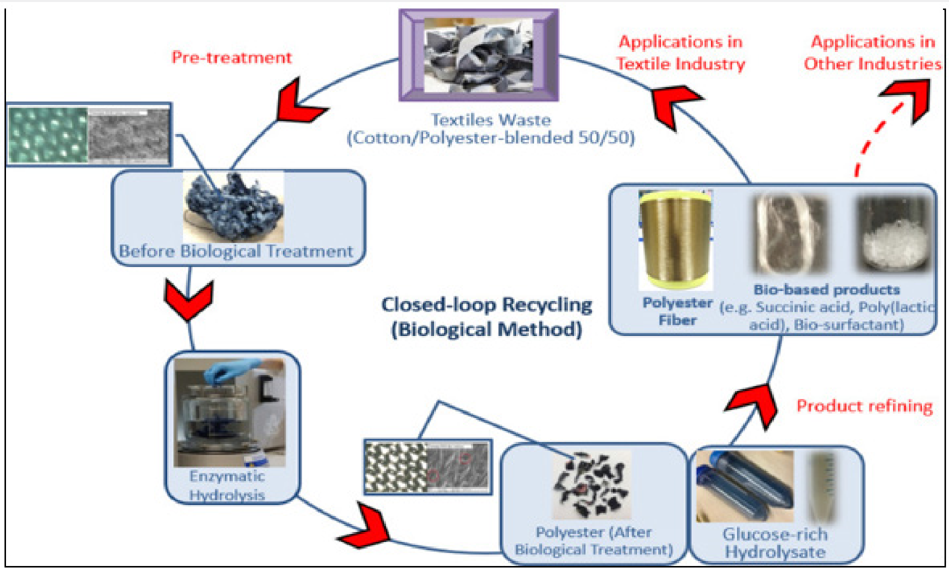

Figure 5: Closed Loop Recycling.

Robotic sorting technology

The textile waste management is seeing an increased use of artificial intelligence (AI). Textiles may be quickly and correctly analyzed by AI-powered sorting systems based on brand labels, colour, and fiber type, which optimizes the sorting process for accuracy and efficiency. This makes it possible to recycle and upcycle sorted materials in more focused ways. ECOPICK is a robot based on artificial intelligence (AI) that recognizes and classifies various objects on a conveyor belt, replacing the tasks usually performed by a manual picker. It is designed to extract textile from MSW (municipal solid waste) flows (Figure 6).

Figure 6: Ecopick.

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Electrostatic separation

It is a promising technique for sorting textile waste based on the material's electrical conductivity properties. It involves

a) **Triboelectric Charging:** When different fibres rub together, they exchange electrons, acquiring opposite electrical charges. For example, polyester becomes negatively charged, while cotton becomes positively charged.

b) **Separation Process:** The textile mix is fed into an electrostatic separator. A high-voltage electrode creates an electric field. The charged fibres experience a force that attracts or repels them depending on their charge and the electrode's charge.

c) **Sorting:** They get separated into different collection chutes based on the fibber's charge and interaction with the electric field.

This technique leads to the effective separation of different fibre types, especially those with contrasting electrical conductivity, like synthetics and natural fibres. Since no water is involved, it becomes an environmentally friendly option. It can handle even tiny fibres that might be difficult to separate with other methods. However, there are certain considerations and challenges like separating complex blends with multiple fibre types might require additional sorting steps, moisture content in the fibres can affect the triboelectric charging and separation efficiency. Also, textile waste might need shredding or size reduction for optimal separation. This technology is currently more commonly used for separating plastics, but research is ongoing for its application in textiles [23].

Laser-induced Breakdown spectroscopy (LIBS)

LIBS is a powerful technique emerging as a tool for textile waste management [24].

a) **Laser Pulse:** A focused laser pulse hits the textile sample, creating a tiny, hot plasma cloud.

b) **Elemental Fingerprint:** The excited atoms in the plasma emit light at specific wavelengths unique to their elements. This emission spectrum acts like a fingerprint for the material's composition.

c) **Spectral Analysis:** The emitted light is collected and analysed by a spectrometer, which separates the light into its constituent wavelengths.

d) **Material Identification:** By comparing the spectrum with a database of known material spectra, the textile fibre type (e.g., cotton, polyester, nylon) can be identified.

LIBS provides quick identification of fibre types, allowing for faster sorting of textile waste. The technique is non-destructive as it requires minimal sample preparation and does not damage the material, making it suitable for sorting even delicate textiles. It can identify not only the main fibre types but also dyes, finishes, and other additives present in the textile.

However, LIBS equipment can be expensive compared to some traditional sorting methods. Interpreting the complex spectral data from LIBS requires advanced software and expertise, which may limit its widespread adoption. While promising, LIBS for textile waste sorting is still under development. More research is needed to optimize the technique for various textile blends and complex compositions.

Magnetic separation

Natural and synthetic fibers like cotton, polyester, nylon, wool, and linen are non-magnetic and will not be attracted to magnets for separation. Despite the limitation, magnetic separation can be a valuable tool in two key scenarios [25].

a) **Removing Ferrous Metal Contaminants:** Often, textile waste streams contain zippers, buttons, rivets, and other metallic components made of ferrous metals (iron and steel). Magnetic separation effectively removes these unwanted elements before further processing the textile fibers. This improves the quality and purity of the recycled fibers and safeguards machinery during subsequent recycling steps [26,27].

b) **Sorting Blended Fabrics with Metallic Fibers:** Although uncommon, some textiles incorporate metallic fibers for specific functionalities like anti-static properties or heat regulation. Magnetic separation can be useful for separating these blended fabrics from purely non-metallic ones. The metallic fibers would be attracted to the magnet, allowing for some level of segregation.

Some common magnetic separation devices used in textile waste processing include

a) **Overband Magnets:** Powerful magnets suspended above conveyor belts carrying the textile waste. Ferrous metals are pulled towards the magnet and removed from the waste stream.

b) **Magnetic Pulleys:** Conveyor belt pulleys wrapped with magnets. As the waste passes over the pulley, ferrous metals are attracted and stick to the belt, separating them from the non-magnetic fibres.

X-ray Technology

X-ray technology itself is not for physically separating textile waste, but it acts as a helpful analytical tool. There are two main ways X-rays are used in textile waste sorting [28].

X-ray Fluorescence (XRF) Sorting:

XRF analysis exposes the textile waste to X-rays. Each element within the fibers has a unique atomic structure and emits its own characteristic X-ray (fluorescence) when hit by X-rays. By analyzing the fluorescent X-rays, the XRF scanner can determine the chemical composition of the fibers. This allows differentiation between natural fibers (cotton) and synthetic fibers (polyester,

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nylon, etc.), crucial for separating blended fabrics for proper recycling. XRF can also detect the presence of dyes, finishes, and other additives used in textiles. This information helps direct the waste to appropriate recycling streams or identify potential contaminants. While XRF is powerful, it might not be able to perfectly distinguish between fibers with very similar atomic structures, like some types of nylon and polyester [29].

X-ray Absorption Sorting:

This method uses X-rays of varying wavelengths. Different materials absorb X-rays to different extents depending on their density and atomic structure. It analyzes the overall density of the material passing through the X-ray beam. This helps separate different fiber types based on density variations. For instance, separating natural fibers (generally less dense) from synthetic ones (often denser). X-ray absorption might be ineffective in differentiating between fibers with very similar densities [30,31].

Summary

The variety of blends, colours, treatments, and accessories on textiles contribute to the heterogeneity and complexity of textile waste, making trash sorting and separation challenging. Innovative approaches are explored to manage textile waste in response to the environmental challenges posed by the textile industry. It discusses traditional mechanical and chemical separation methods and cutting-edge technologies like biological separation, electrostatic separation, and laser-induced breakdown spectroscopy. Combining electrostatic separation with other sorting techniques like air jet separation or optical sorting might be necessary for a more comprehensive textile waste recycling process. X-ray-based sorting offers a non-destructive way to analyze textile waste's chemical composition and density. This information is crucial for separating blended fabrics and directing them to appropriate recycling streams. This ultimately contributes to a more sustainable textile industry by ensuring proper recycling of different fiber types.

The review underscores the significance of sustainable practices in the textile sector to mitigate waste accumulation and environmental impact associated with fast fashion. It emphasizes the importance of adopting advanced separation techniques to facilitate the recycling and upcycling of textile materials, promoting a more circular and environmentally conscious fashion industry. By implementing these strategies, the textile sector can reduce its ecological footprint, minimize landfill waste, and contribute to a more sustainable future for industry and the planet.

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