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Advancements in the Development of Sustainable (Textile) Materials and their Recycling Methods

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Abstract

Due to inadequate recycling systems and the complex nature of textile products, each year, millions oftonnes of textile waste end up in landfills or are incinerated globally. This paper seeks to highlight theadvancements in sustainability for textile materials, focusing on cotton and polyester, and analyse theirrespective recycling methods to identify strategies for reducing the annual production of textile waste.Environmental issues raised by textile materials are also considered, such as the non-biodegradability of polyester and the large amount of freshwater used in cotton production. This study examines innovative materials that can substitute traditional fibres, such as organic cotton and bio-based polyesters, highlighting their role in reducing the environmental impact of textile production. Additionally, the paper evaluates various recycling methods for these fibres and their effectiveness inmanaging textile waste. It was analyzed that there has been a fivefold increase in publications of textile recycling from 2011 to 2021, reflecting rising global interest and progress. The trend towardssustainable fashion, embraced by many brands, highlights an increase in customer demand for eco- friendly choices and aims to minimise the industry's environmental impact. Conclusively, further research must optimize technology to develop new sustainable materials while simultaneously maintaining an affordable price to encourage the purchase of these products among consumers.

Keywords: *Textile, Fibres, Cotton, Polyester, Sustainability, Recycling, Environment*

1. Introduction

Over the years, the global demand for textile materials has surged dramatically, leading to vast levels of textile waste. In 2013, the worldwide consumption of textile fibres was approximately 85.5 million metric tonnes, and it is projected to reach over 130 million metric tonnes by 2025 [1]. Fig. 1 below shows the increase in fibre production over the past four decades [2].

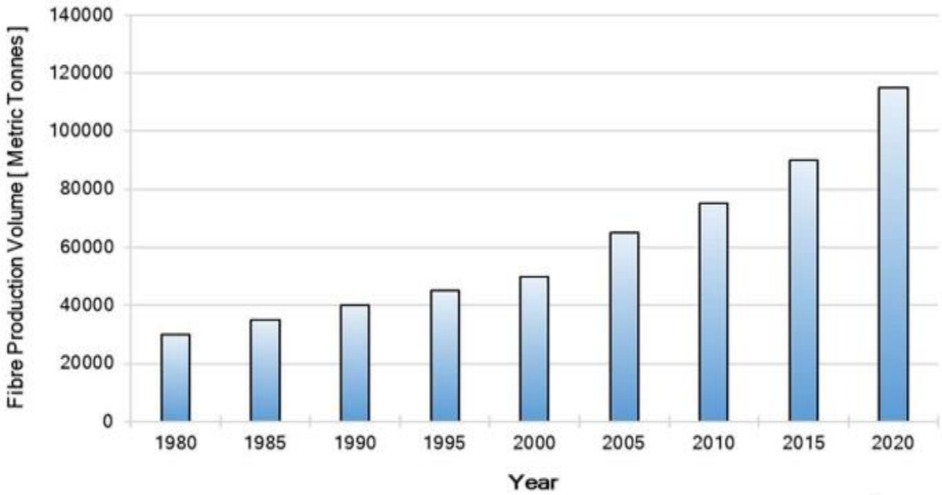

Figure 1. Fibre Production Volume from 1980 to 2020 (inclusive)

This rise in consumption is closely linked with the growing global population, improving living standards, and rapidly changing fashion trends in recent times. Due to this, several sustainable materials and recycling methods have been developed.

Textile fibres are broadly divided into the following two categories:

1. Natural fibres: obtained from plants and animals (e.g. cotton, wool, jute, bamboo.)
2. Synthetic fibres: man-made fibres that are produced through a series of chemical synthesises, usingpetroleum (e.g. polyester, nylon, acrylic.)

As illustrated in Fig. 2, synthetic fibres account for approximately two-thirds of global textile fibre consumption, with polyester dominating more than half of this market share [3].

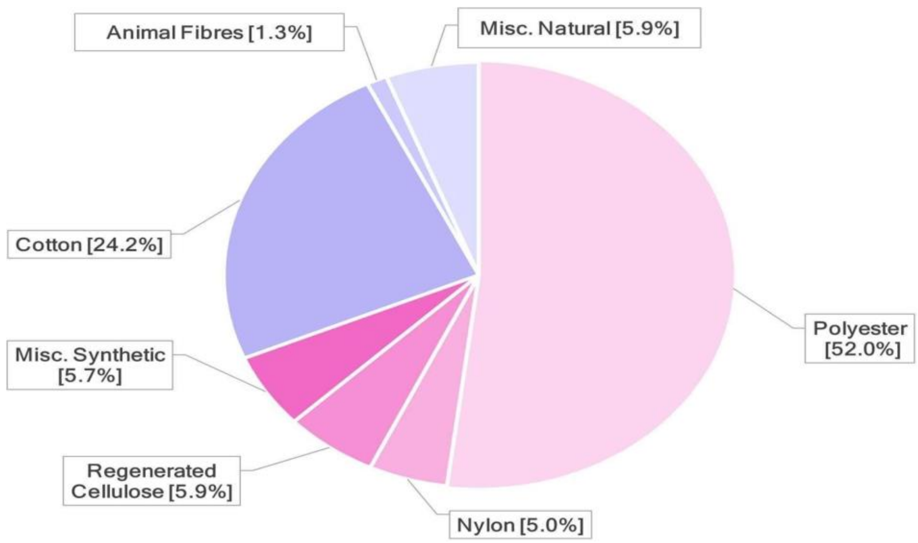

Figure 2. Textile Fibres Market Share (2020)

Natural fibres are derived from renewable resources. However, despite common belief that they are inherently sustainable and organic, this is not always the case. For example, cultivating cotton fibre requires a substantial amount of freshwater, typically between 8,000 and 22,000 litres per kilogram of fibre produced. Additionally, cotton plants need large quantities of pesticides and insecticides. Around 11% of the world's pesticides and 26% of its insecticides are used in cotton production [2].

This leads to environmental issues such as soil erosion, water pollution, and increased greenhouse gas emissions. Additionally, the production of fabrics from natural fibres—through stages like ginning, spinning, weaving, and processing—requires the use of various toxic chemicals, large amounts of freshwater, and significant energy, particularly during processing stages such as bleaching, dyeing, and finishing. As a result, the production process is unsustainable.

On the other hand, synthetic fibres are considered a threat to the environment due to their non- biodegradable and non-renewable nature. The production of synthetic fibres depletes resources, as these fibres are made from non-renewable sources like petroleum and petrochemicals. The manufacturing of polyester is more environmentally friendly than cotton in terms of water usage and the release of toxic chemicals into water and land. However, producing polyester requires nearly twice as much energy as producing natural fibres like cotton, thereby contributing to global warming [2]. Moreover, large amounts of emissions of volatile organic compounds (VOCs), particulate matter, and acid gases such as hydrogen chloride are released, which aggravate respiratory diseases [4]. Nylon, another synthetic fibre, requires about three times the energy compared to cotton for its manufacturing. It also releases nitrous oxide, which is a greenhouse gas that depletes the ozone layer more significantly than carbon dioxide. Along with polyester, nylon generates microfibres, which lead to marine pollution [2].

Due to the issues mentioned above, the textile industry is recognised as the fifth largest contributor to carbon emissions, accounting for about 10% of global emissions. Worldwide, approximately 75% of textile waste ends up in landfills, with the remainder being reused or recycled—though less than 1% of total textile waste is recycled into new clothing [5]. The ongoing rise in textile consumption and its adverse environmental impact highlights the urgent need to change how we manage textile waste.

2. Materials and Methods

This section of the research paper intends to highlight the development of methods used to recycle the textile waste and improve industrial sustainability. Since polyester and cotton collectively make over 75% of the total market share of textile fibres, this paper will solely focus on the sustainability developments of these fibres.

2.1. General Recycling Terms and Methods

Sorting is the first step in textile waste recycling since it is critical to remove contaminants from the fibre, which would otherwise detriment the quality of the recycled fibre. While textile sorting is often carried out manually, use of automated technology is more economical in areas with high labour costs. The most advanced methods are infrared (IRS) and near-infrared (NIRS) spectroscopy, which detect differences in chemical composition between fibre types. They offer quicker response times and can distinguish various textile types from each other, even with minimal spectral differences.

Mechanical recycling entails physically sorting and shredding waste materials, then melting the thermoplastic polymer to create clean resin pellets, which are then used as raw materials for the production of other fibres. Chemical recycling involves breaking chemical bonds and converting polymers back into their monomer states.

There are two primary frameworks for recycling in the industry: open-loop and closed-loop recycling. Open-loop recycling focuses on collecting and reusing materials, often into products of lower quality or value than the original, which are eventually disposed of. Delaying the final disposal of materials helps cut down on the total waste since it reduces the need to produce new materials for other applications.

In contrast, closed-loop recycling involves reprocessing materials in ways that maintain their properties and value so they can be reused within the same product value chain, such as fibre-to-fibre recycling.

Although closed-loop recycling of other materials, such as glass and paper is well-established, closed-loop recycling of post-consumer textile is just beginning to gain momentum thanks to technological and logistical advancements. Fig. 3 shows a visual representation of open-loop and closed-loop recycling [11]. For both methods, a combination of mechanical and chemical recycling is usually used.

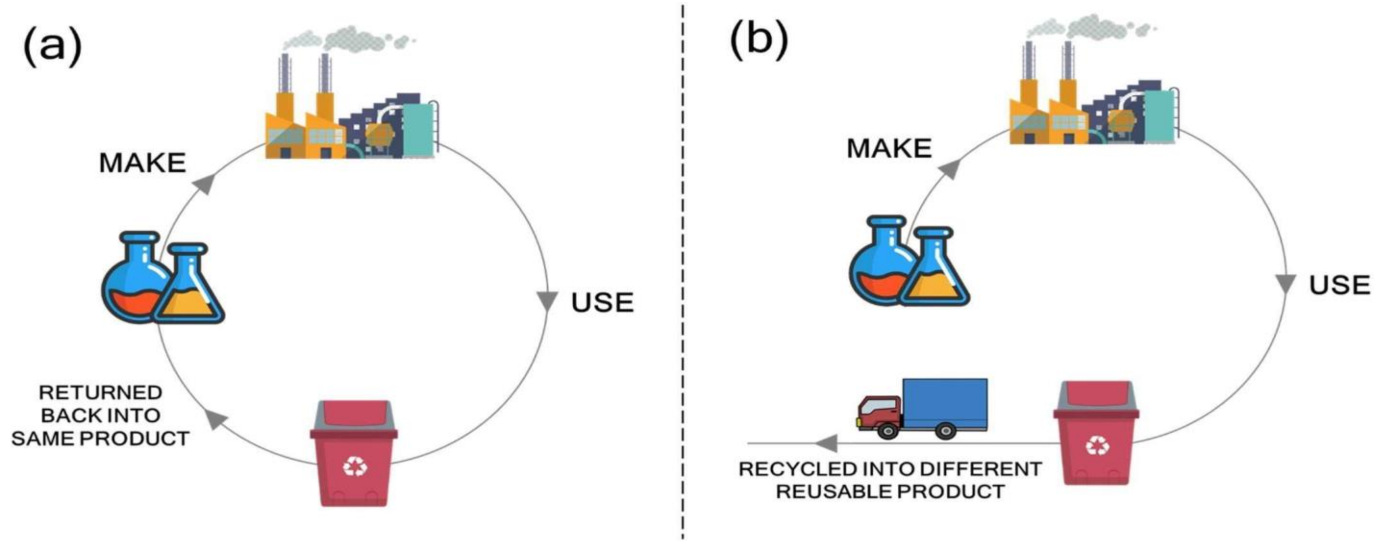

Figure 3. Visual representation of (a) Open-Loop and (b) Closed-Loop Recycling

Over time, repeated use and recycling will lead to significant polymer degradation and a decline in material properties. Chemical recycling is the optimum solution to this problem.

3. Discussion

This section of the paper discusses the sustainable development and recycling methods of polyester and cotton.

3.1 Polyester

Most polyester fibre is made from poly(ethylene terephthalate) (PET), which is valued for its high strength, resistance to chemicals and wrinkles, and quick-drying properties. It is a synthetic polymer obtained from condensation polymerisation, in the presence of a catalyst, of two monomers: terephthalic acid (TPA) and ethylene glycol (EG).

PET textile fibres can be obtained through mechanical recycling of PET bottles or other PET packaging materials, which is the most common method of recycling PET products. Among other plastics, PET has the most advanced post-consumer recycling infrastructure. The first step involves collecting and sorting PET plastic. This is followed by washing, which includes soaking the PET plastic waste in a solution of water and detergent to remove any impurities. After being mechanically shredded with a shredder machine, the materials are ground into finer particles, resulting in loose fibres that can be used for fillers or nonwoven fabrics.

The third stage again involves washing, which eliminates contaminants from post-consumer PET waste, followed by separation to isolate PET materials from other plastic polymers and non-plastic substances. This ensures the production of high-quality recycled PET materials only. The final stage includes drying the materials to eliminate moisture. They are then melted to produce molten PET resin. This process guarantees the integrity and high quality of the recycled materials, making them suitable for a range of industrial applications. During the melting of bottle chips, polymer molecular weight and intrinsic viscosity decrease, which prevents the recycled PET (rPET) from being reused for bottles. However, the resulting resin still has properties suitable for being converted into textile fibres.

Chemical recycling of PET is an emerging technique used for achieving closed-loop recycling. Chemical recycling includes processes such as depolymerisation, purification, re-polymerisation, andquality control. Depolymerisation includes heating PET with an access of methanol and a catalyst, causing the PET to break down into its constituent monomers (TPA and EG). Purification is the processof removing impurities or contaminants. Re-polymerisation uses heat and a catalyst, forming the recycled fibre. Lastly, quality control ensures the final product meets required standards for strength, durability, and appearance [9].

Unlike mechanical recycling, chemical recycling preserves the properties of the original fibre and prevents thermal degradation, resulting in higher-quality rPET. This is because the process ultimately recovers small-molecule monomers rather than large complex polymers. It also allows greater flexibility in the types of recycled products made. Chemical recycling reduces greenhouse gas emissions and energy consumption by up to 50% compared to virgin PET production [9]. As the demand for recycled PET (rPET) grows, advancements in efficient and economical chemical recycling processes are likely to become a key focus of research and development.

There have been numerous such advancements regarding recycling of PET in the past few years. Using a glycolysis route (also called alcoholysis) in the presence of sodium sulphate as a catalyst, depolymerisation of PET produces a good yield of bis(2-hydroxyethylene terephthalate) (BHET). To attempt its reuse, a promising method has been discovered to recycle waste PET fibres into other textile additives by converting BHET into quaternary ammonium compounds, which can serve as softeners in the cotton finish process [10].

Microbes and enzymes can depolymerise PET in an eco-friendly way. Researchers at TBI (Toulouse Biotechnology Institute) and Carbios collaborated on an enzyme-based degradation technology, achieving 90% conversion of coloured PET flakes (approximately 60% crystallinity) in under 10 hours [6]. This technology may be applicable for recycling of PET fibres; however, it would require pre- treatment steps, such as extrusion and micronisation, and hydrolysis conditions of -72 °C to decrease PET crystallinity and increase the accessible area of enzyme reactions [6].

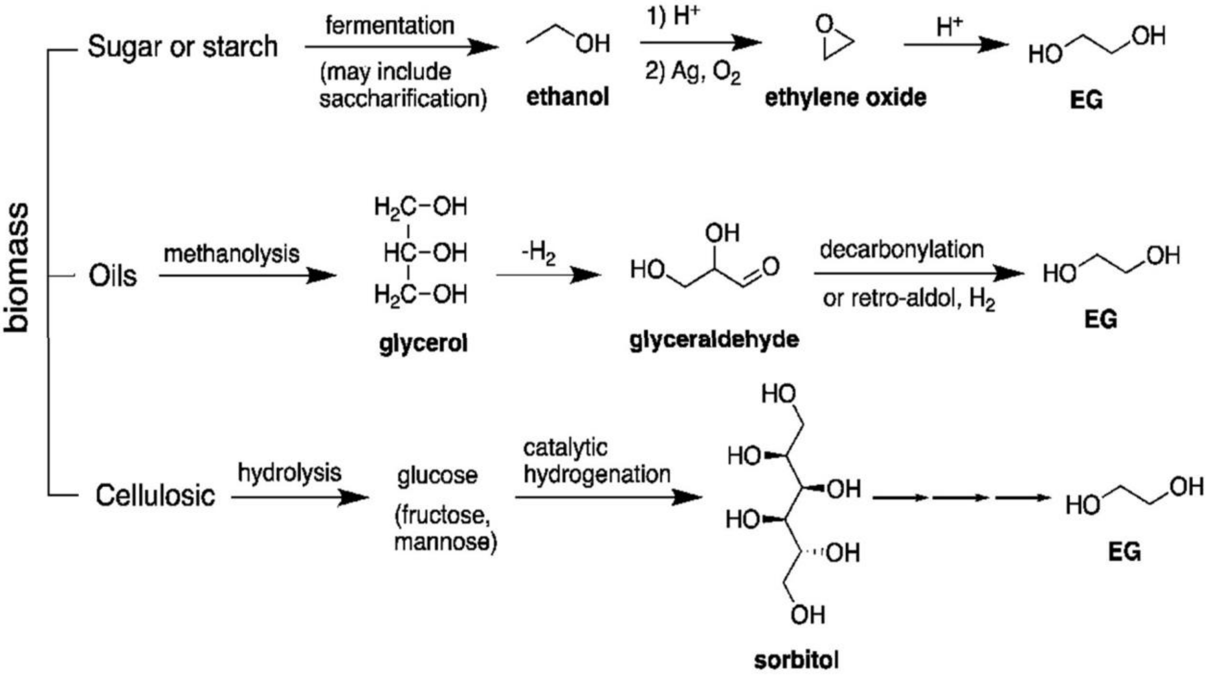

Figure 4. Chemical Synthesis of Bio-Based EG from Three Different Raw Materials.

Bio-based polyesters are formed from bio-based monomers, which are obtained from renewable resources. Due to their wide range of applications and environmentally friendly behaviour, bio-based polyesters have attracted a great deal of interest. In recent years, with the advancement of more mature technologies for production of bio-derived monomers, several bio-based polyesters have emerged in the rapidly expanding bio-based industry. Synthesis of bio-based EG (a monomer of PET) occurs from renewable resources such as ethanol, glycerol, sugars, etc. Fig. 4 shows chemical reactionsin forming EG through three different biomass raw materials [6].

The other monomer, bio-based TPA, requires a longer synthesis. Bio-based p-xylene is an important intermediate that can be converted to TPA through catalytic oxidation; however, it is difficult to produce it. The company “Origin Materials” has developed a method to convert lignocellulosic biomass to 5(chloromethyl)furfural (CMF), which is a precursor to p-xylene [6]. Bio-based CMF serves as a versatile precursor for producing various products, such as cyclohexanone, caprolactam, and hexamethylenediamine. Fig. 5(a), overleaf, shows the reaction pathway of production of p-xylene from CMF [6]. P-xylene or TPA can be obtained through different routes, besides the ones shown in Fig. 5(a). Bio-ethylene, isobutanol, and isoprene are some raw materials that can be used forthe synthesis.

Fig. 5(b) shows the process of obtaining p-xylene or TPA from isoprene. It begins with a DA reaction, followed by dehydro-aromatisation and oxidation, giving the target product, the TPA monomer.

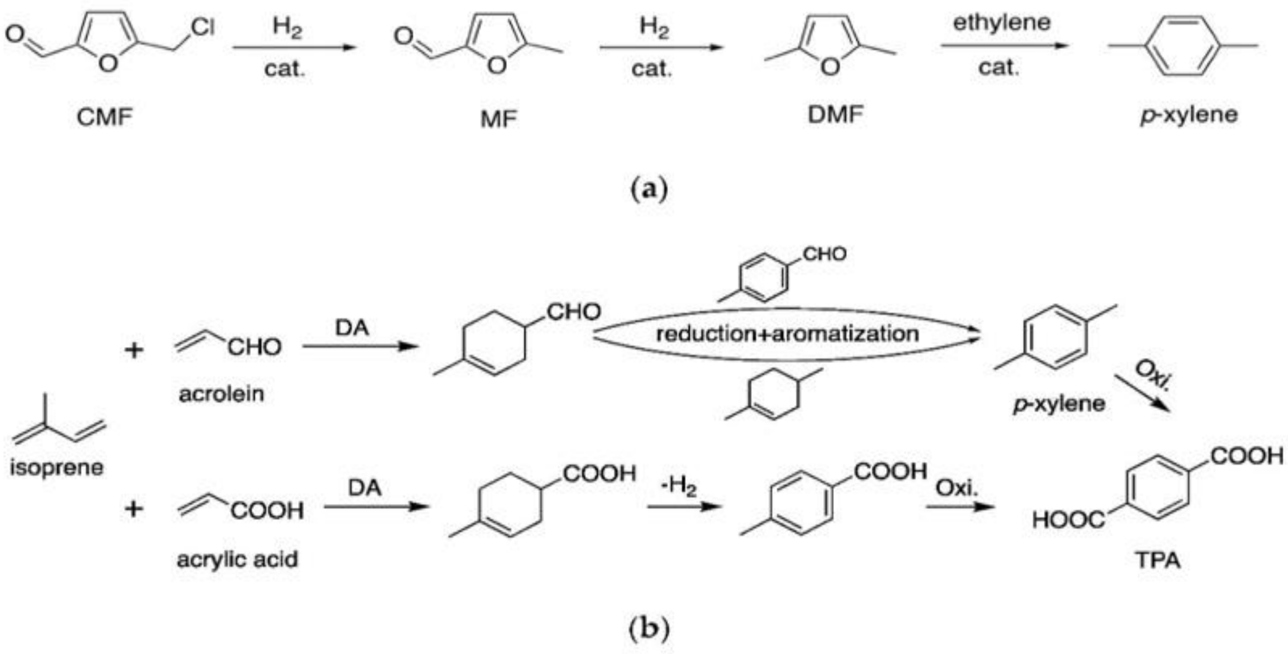

Figure 5. Chemical Pathways to Produce p-Xylene; (a) From CMF to p-Xyleneand (b) From Isoprene to p-Xylene or TPA

Widely used bio-based polymers, such as poly(lactic acid) (PLA), polyhydroxyalkanoates (PHAs), and poly(glycolic acid) (PGA), all classified as aliphatic polymers, lack rigidity due to their innate structure,which results in weaker thermomechanical properties compared to oil-based polymers, suchas poly(ethylene terephthalate) (PET) and polycarbonates (PC). Hence 2,5-Furandicarboxylic acid (FDCA), which is a rigid di-acid sourced from lignocellulose and fructose, shows significant potentialas an alternative to terephthalic acid (TPA). Poly(ethylene 2,5-furancoate) (PEF) is produced as a resultof using FDCA [12]. Since FDCA is produced from the oxidation of 5-hydroxymethylfurfural (HMF), which is formed fromlignocellulose and fructose, its synthesis is sustainable, which is one of the reasons for the growing popularity of FDCA in bio-based polyesters.

A life cycle assessment revealed that PEF production reduces non-renewable energy use and greenhouse gas emissions by approximately 50% compared to PET production [13]. Other than its sustainability benefits, its similarities to TPA are also beneficial. However, the minor differences in their ring size, polarity, and geometry differ the polyesters in performance aspects. Moreover, the rigidity of FDCA due to its five-membered ring improves its thermomechanical properties [12].Fig. 6 shows the structural formula of FDCA and TPA.

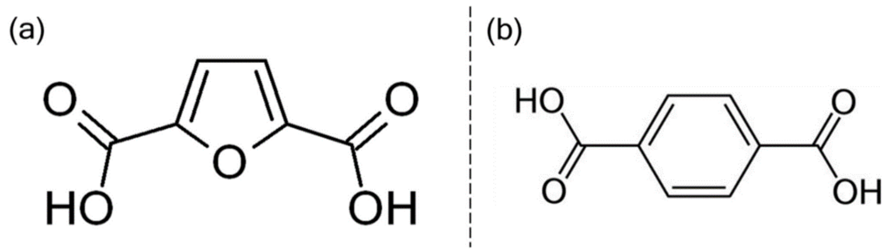

Figure 6. Structural Formula of (a) FDCA and (b) TPA

3.2. Cotton

Cotton fibres, a type of natural fibre, are seed hair derived from plants belonging to the genus Gossypium. They have ribbon-like shapes that enable them to form strong yarns. The cells develop a thick wall that mainly consists of cellulose, with smaller amounts of protein, wax, pectin, and other trace substances. The multiple layers of cellulose microfibrils in the cell wall contribute to their fibre strength. Cellulose, which is a biopolymer, is synthesised from glucose monomers activated by uridine diphosphate (UDP) in a simultaneous synthesis and translocation process across the cell membrane. Popularity of cotton fibres mainly results from its comfortability and softness and becauseit has high water absorption and breathability.

The main concern for cotton recycling is the reduced quality of the recycled fibre. *Mechanical recycling*of cotton involves processing waste by cutting, shredding, and combining waste cotton to retrieve intactstaple-length fibres, which are then re-spun. However, fibres spun from mechanically recycled cotton are of lower quality compared to virgin fibres. The harsh forces required to break down tightly twistedcotton yarns cause fibre damage and breakage, resulting in shorter fibre lengths. Consequently, the strength and tactile properties of the final products decrease [6].

Mechanically recycled cotton fibres of sufficient length (≥ 13mm) can be blended with virgin cotton to enhance the quality of recycled yarn while lowering the cost of raw materials for virgin yarn. However, such short-recycled cotton fibres usually require a higher proportion of virgin cotton to meetthe quality standards for garment applications. Shorter fibres (< 10mm) can be used as reinforcement in composites [6]. Cotton fabric waste can also be incorporated into nonwovens, acoustic insulation, and building materials through mechanical recycling. In one instance, cotton waste fibres were processed through mechanical recycling methods, including needle punching, and formed into a continuous web of nonwoven fabrics [12]. Moreover, mechanically recycled cotton waste can be formed into other applications, such as paper pulp. In an experiment, handsheets of 70 g/m^2 and80 g/m^2 were produced from cotton waste [13].

Chemical recycling of cotton converts natural cotton fibres into regenerated cellulose fibres, achieving closed-loop recycling. Researchers from Deakin University have developed a chemical recycling process for cotton, wherein waste denim is dissolved in a binary solvent and then spun into regeneratedcellulose fibre. The process utilises dimethyl sulfoxide (DMSO) as a co-solvent with ionic liquid 1- butyl-3-methylelimidazolium acetate for the dissolution of the denim waste. This method enables the spun fibre to regenerate the original colour of the waste garment, which can be removed from a long NaOH treatment if required, eliminating the need for re-dyeing [14].

Using this method prevents the use of significant amounts of water and energy, which are typically used in traditional textile dyeing processes. The regenerated cellulose fibre exhibits properties like viscose fibre. However, due to its relatively high molecular weight, it possesses lower stretch and higher wet tenacity. The solvents used may be recovered and recycled in a closed-loop system [14].

Combining both mechanical and chemical recycling of waste cotton can enhance material utilisation and provide additional opportunities for co-product applications that capitalise on the altered fibre length and degree of polymerisation (DP) resulting from recycling processes. For example, short cotton fibres generated through mechanical recycling can be used as reinforcement in composites, which is apotential high-value application [6].

Cotton waste that is not suitable for other applications can be usedfor *energy recovery.* In waste management, “recovery” refers to extracting embedded chemical energyfrom materials that are otherwise non-recyclable, achieved through incineration or converted to energyby other means. For instance, when the quality of fibre or cellulose degree of polymerisation (DP) is insufficient for recycling through other methods, cotton waste can undergo hydrolysis to yield glucose.This glucose can then serve as a fermentation feedstock to produce bioenergy or other bio-based products [6].

One reason cotton is considered unsustainable is the extensive use of chemicals and pesticides in its production; thus, *organic cotton* serves as a more sustainable alternative. Since organic cotton is grownnaturally, it helps preserve biological diversity in agriculture by significantly reducing the use of fungicides and pesticides, hence supporting a range of life forms. Organic cotton production systems rely on biological substances rather than chemicals, unlike conventional farming methods. Inorganic fertilisers are replaced by organic alternatives, such as farmyard manure, green manure, compost, etc., and the process commonly utilises herbicides and pesticides of botanical origin, such as ipomoeaand neem cake. The use of chemical defoliants is also avoided in the harvesting of organic cotton [15]. Fig. 7 shows the biological inputs in organic cotton cultivation [16].

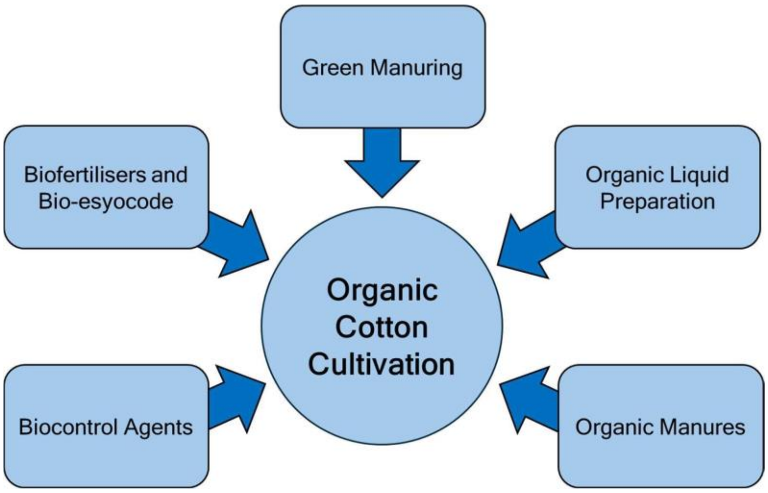

Figure 7. Biological Inputs in Organic Cotton

Organic cotton production avoids the use of toxic chemicals, creating a healthier environment for farmers and reducing environmental pollution. Additionally, soil fertility is preserved since its composition remains unaffected by chemicals. Organic cotton production also eliminates the need to treat the water contaminated with chemicals, as organic processing uses only simple, non-toxic dyes instead of hazardous chemicals such as chlorine, toxic finishes, or bleach [15]. By avoiding the use of agrochemicals, the production of organic cotton is more economical and has lower production costs. However, organic cotton has a lower yield compared to traditional cotton, resulting in a higher market price for organic fabric.

4. Conclusion

The advancements in sustainable textile materials and recycling methods mark a significant step forward in addressing the environmental challenges faced by the textile industry. Innovative materials like organic cotton and bio-based polyesters contribute to the industry's sustainability and play a crucial role in reducing the vast amounts of textile waste generated annually.

A bibliometric analysis of the Web of Science database shows that the number of publications on textile recycling has increased more than five times from 2011 to 2021. This trend clearly indicates a growing awareness of textile waste and demonstrates that both public interest and progress in recycling efforts have significantly increased over the years.

Moreover, "sustainable fashion" has become a trend embraced by numerous clothing brands, leading them to introduce eco-friendly products into the market. This movement not only reflects a growing consumer demand for environmentally responsible choices but also aims to reduce the environmental impact of the textile industry and promote a more sustainable future for fashion.

While considerable progress has been made towards sustainability, future research should aim to optimise technologies for greater production efficiency and develop new materials that can further enhance sustainability. Additionally, efforts should be made to keep market costs low to ensure these advancements are accessible to environmentally conscious consumers.

5. Acknowledgement

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